

# Flavor as a Portal beyond the Standard Model

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# Introduction - Flavor as a portal beyond the SM

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- Besides the **hierarchy problem** (mechanism of EWSB) and the **dark-matter puzzle**, the **origin of flavor** is one of the big, unsolved mysteries of fundamental physics
  - ▶ connected to deep questions such as the **matter-antimatter asymmetry** in the Universe, the **origin of fermion generations**, and the reason for the **striking hierarchies** observed in the spectrum of fermion masses and mixing angles
  - ▶ in SM, **flavor physics is connected to EWSB** via the Higgs Yukawa interactions
- Flavor physics is an issue for any extension of the SM (“flavor problem”)

# Introduction - Flavor as a portal beyond the SM

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- For almost two decades flavor physics was largely ignored and considered irrelevant to high-energy discovery physics
- The reason was that SUSY has little to say about the origin of flavor -- and worse, that flavor is potentially problematic for many (generic) SUSY models
- Fortunately, in recent years the situation has changed significantly
- Flavor is now generally viewed as a **key ingredient** of any BSM theory, which may help to **discover New Physics** (even beyond the direct LHC reach) and **decipher its nature**



but see:  
Mu-chun Chen @ SUSY11 (THU)

# Introduction - Flavor as a portal beyond the SM

## Intriguing example: Anomalous top-quark forward-backward asymmetry at the Tevatron

- New Physics contribution from s- or t-channel exchange of a new heavy particle, interfering with SM tree-level contribution
- In all but one model,<sup>\*)</sup> the existence of new heavy particles with **non-trivial flavor structure** is required!

see e.g.:

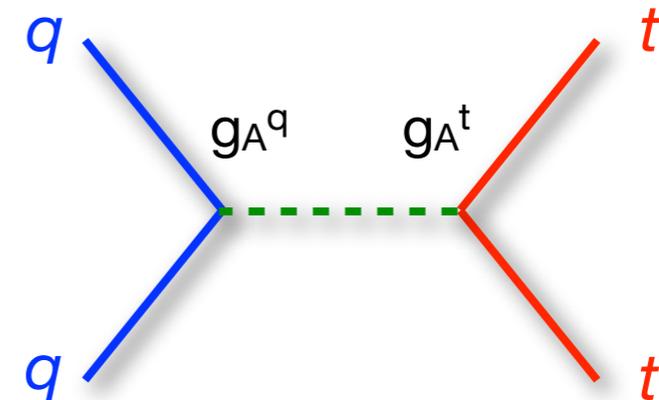
Grinstein, Kagan, Trott, Zupan (2011);

Blum, Hochberg, Nir (2011);

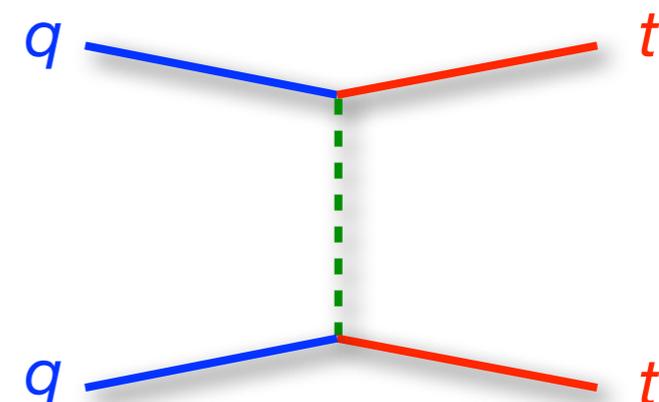
Haisch, Westhoff (2011)

**Martin Bauer @ SUSY11 (THU)**

<sup>\*)</sup> Tavarez, Schmalz (2011): light axigluon model



$\cos\theta$  term  $\propto -g_A^q g_A^t$ , and hence these couplings must have opposite sign ( $g_A^q \neq g_A^t$ )



requires flavor off-diagonal couplings of top to light quarks

# Standard Model and beyond: The Gordian knot

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What is the “New Physics” and how to find it ?

# Standard Model and beyond

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**4<sup>th</sup> generation**



**extended Higgs sectors**



**extended technicolor**



**left-right symmetry**



**leptoquarks**



**universal extra dimensions**



**large extra dimensions**



**warped extra dimensions**



**gauge-Higgs unification**



**Higgsless models**



**MSSM**



**CMSSM**



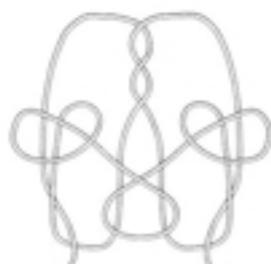
**NMSSM**



**vMSSM**



**SUSY GUTs**



**unparticles**



**Little Higgs**



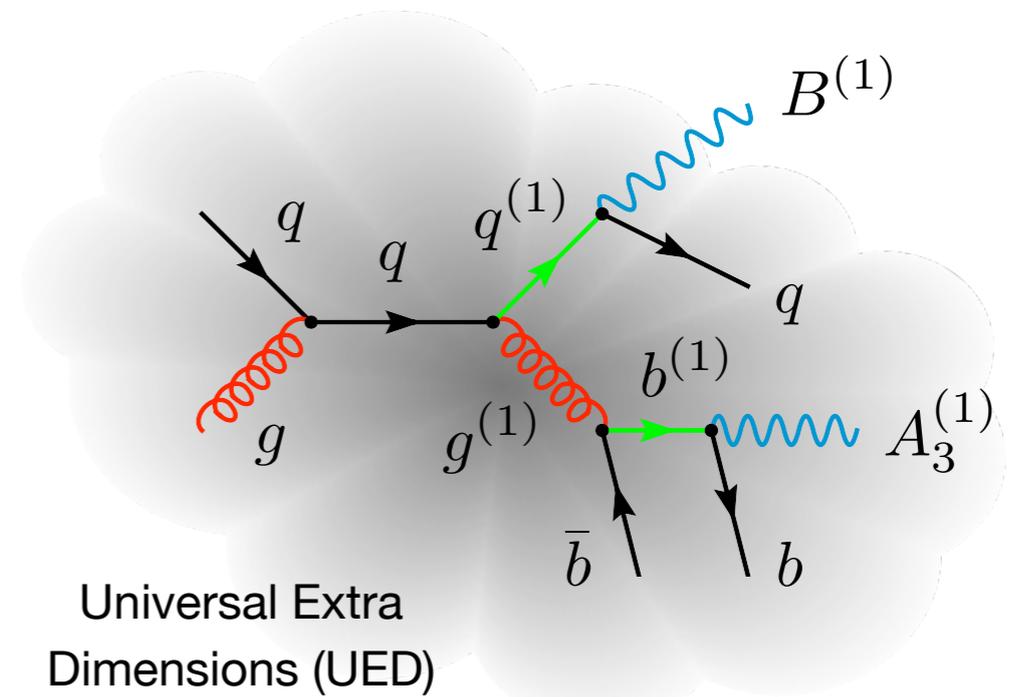
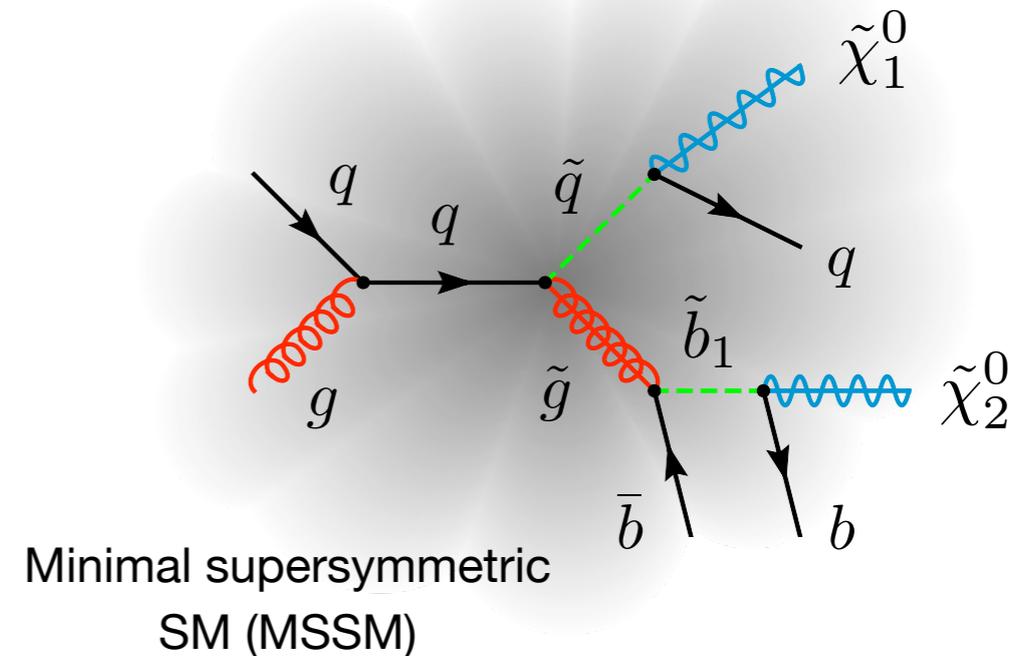
**hidden valleys**



**not yet thought of ...**

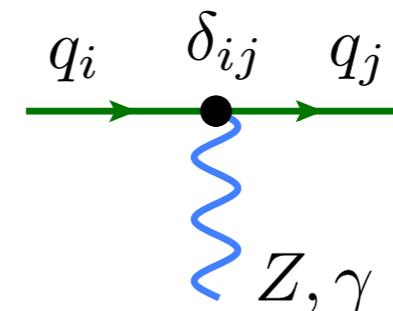
# Complementary of direct and indirect searches

- Production of **new particles** at high-energy colliders probes directly the structure of matter and its interactions
- But quite different scenarios of New Physics can lead to very similar signatures and hence to experimental signals that are difficult to disentangle
- Low-energy precision measurements study quantum corrections from **virtual particles**, offering indirect insights into the structure of matter and its interactions
- In the history of physics, this has often provided **first clues** about a new layer of reality (e.g. weak interactions, charm and top quarks, Higgs boson, ...), since it provides sensitivity to higher energy scales

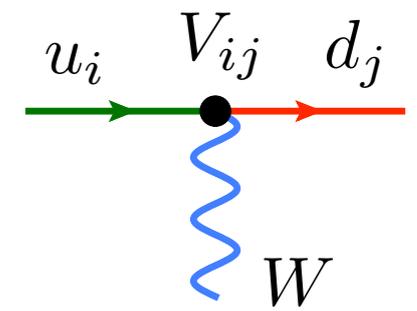


# Legacy of the B factories (BaBar, Belle, CDF, D0)

- Spectacular confirmation of the CKM model as the **dominant source of flavor and CP violation**
- All flavor-violating interactions encoded in Yukawa couplings to Higgs boson
- Suppression of flavor-changing neutral currents (FCNCs) and CP violation in quark sector due to **unitarity** of CKM matrix, **small mixing angles**, and **GIM mechanism** <sup>\*)</sup>



$\delta$ : unit matrix



$V$ : CKM matrix



N. Cabibbo



M. Kobayashi



T. Maskawa

2008 Nobel Prize to Kobayashi, Maskawa

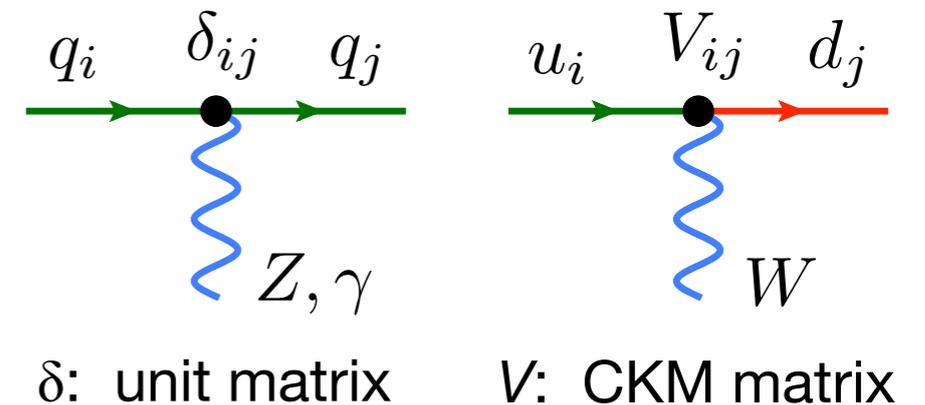
$$V \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \begin{matrix} d \\ s \\ b \\ u \\ c \\ t \end{matrix}$$

$\lambda \approx 0.22$ : Cabibbo angle

<sup>\*)</sup> EPS HEPP Prize 2011 to Glashow, Iliopoulos, Maiani

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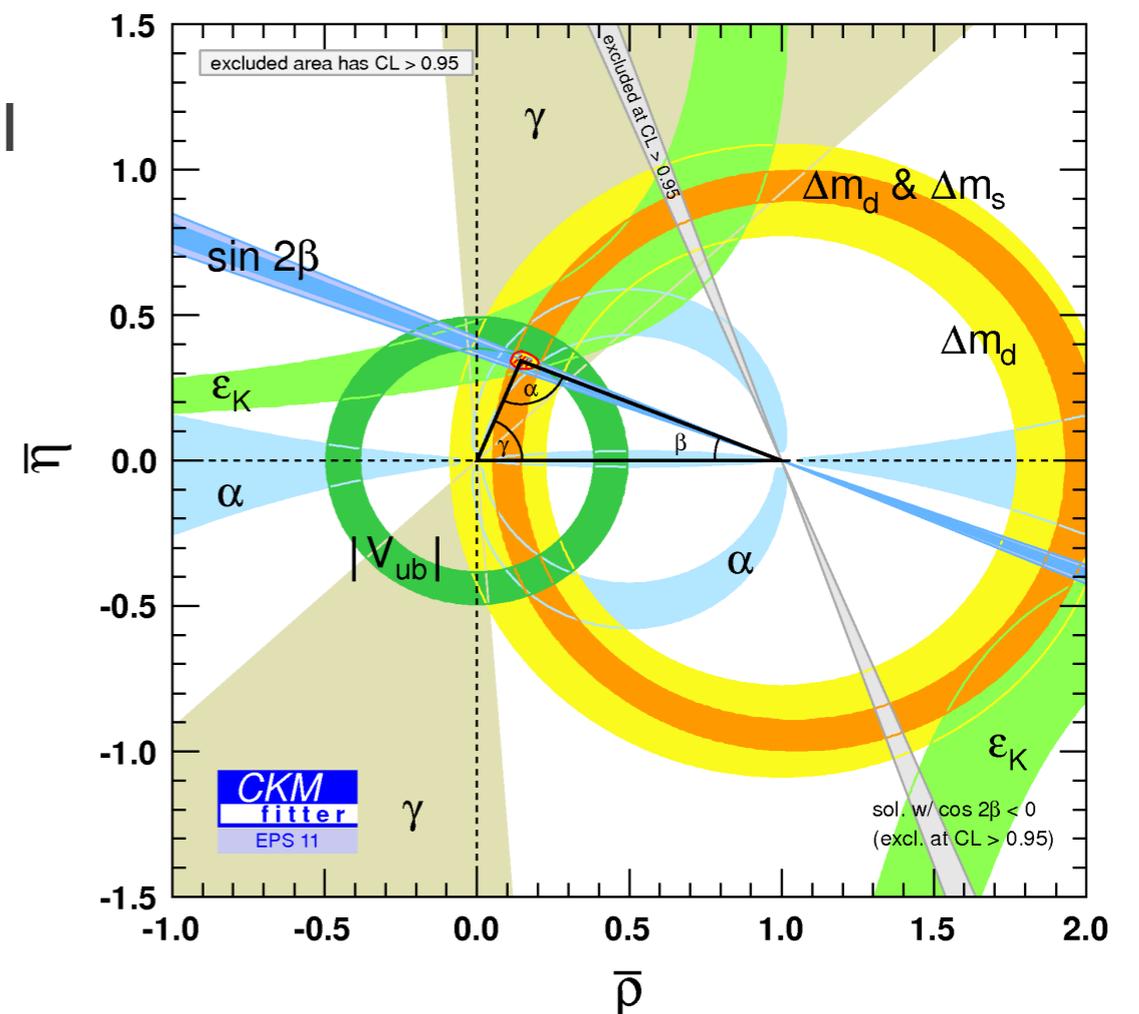


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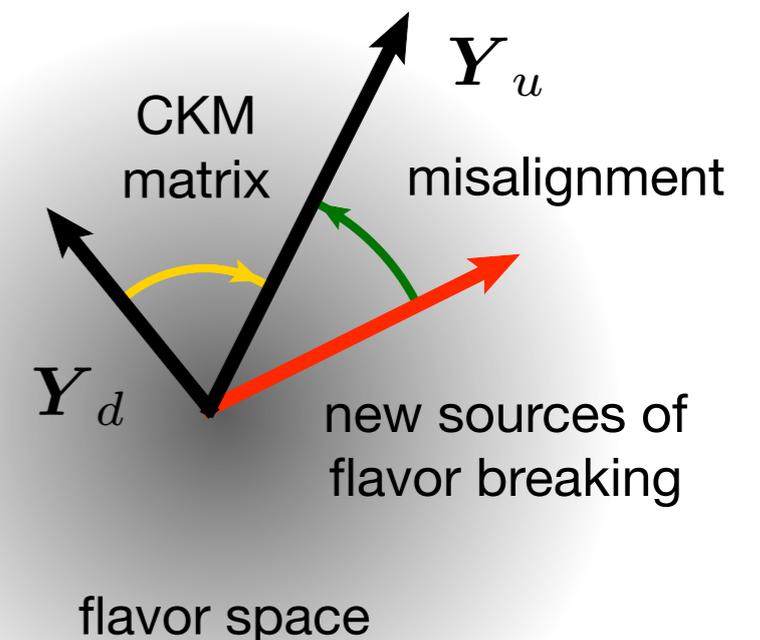
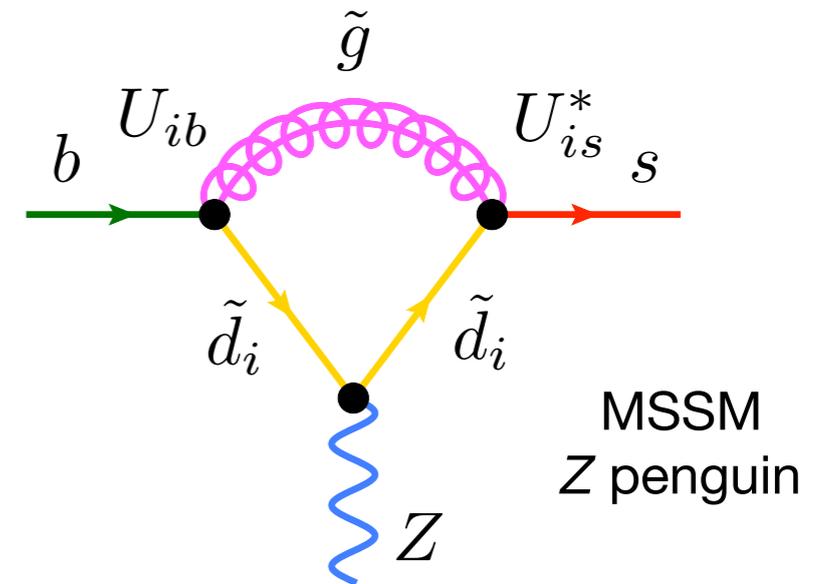
\*) EPS HEPP Prize 2011 to Glashow, Iliopoulos, Maiani

# Flavor structure in the SM and beyond

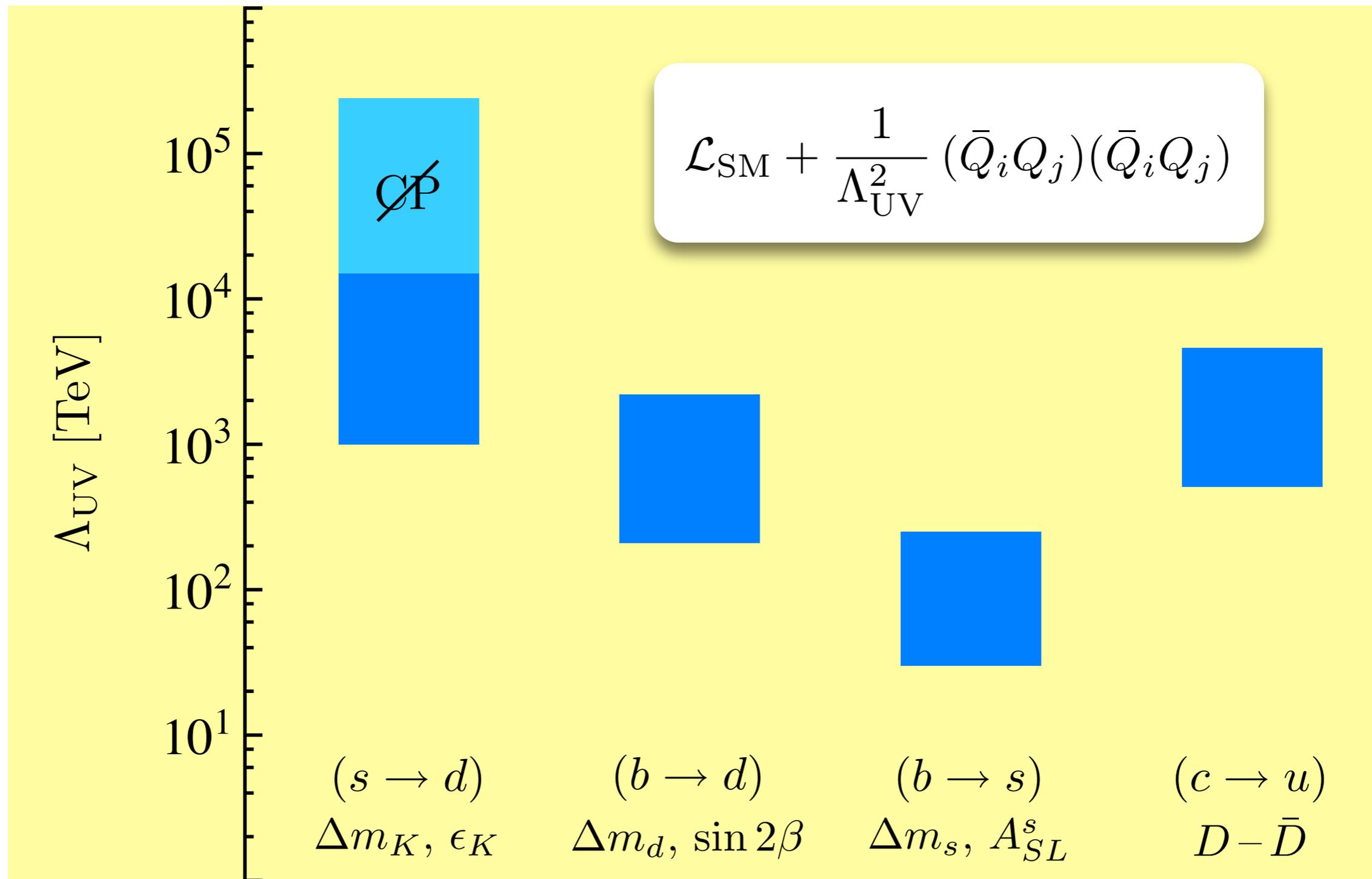
In extensions of the SM, additional flavor and CP violation can arise from exchange of new scalar ( $H^+$ ,  $\tilde{q}$ , ...), fermionic ( $\tilde{g}$ ,  $t'$ , ...), or gauge ( $Z'$ ,  $W'$ , ...) degrees of freedom

- new flavor-violating terms in general not aligned with SM Yukawa couplings  $Y_u$ ,  $Y_d$
- can lead to excessive FCNCs, unless:
  - new particles are very heavy:  $\tilde{m}_i \gg 1 \text{ TeV}$
  - their masses are degenerate:  $\Delta\tilde{m}_{ij} \ll \tilde{m}_i$
  - or mixing angles are very small:  $U_{ij} \ll 1$

**The absence of dominant New Physics signals in FCNCs implies strong constraints on the flavor structure of TeV-scale physics!**



# Flavor structure in the SM and beyond



Generic bounds without a flavor symmetry

# Introduction - Flavor as a portal beyond the SM

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A more refined look indeed shows at some tensions with the SM in several areas of flavor physics:

## $B_d$ -meson system

- Tensions in UT fit
- $V_{ub}$  crisis
- $\sin 2\beta$  tree vs. penguin
- $B \rightarrow \pi K$  puzzle

## $B_s$ -meson system

- CPV in  $B_s$ -meson mixing
- Anomalous like-sign dimuon production
- Rare decay  $B_s \rightarrow \mu^+ \mu^-$

At present, some of the most tantalizing hints (not more) of BSM physics -- besides  $(g-2)_\mu$  and the top-quark forward-backward asymmetry at the Tevatron -- come from the flavor sector!

**We live in exciting times, since many of these hints will very soon be cross-checked and perhaps corroborated at LHC!**

# Flavor phenomenology in extensions of the SM

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- Much recent activity on a variety of models, including:
  - ▶ SUSY models (MSSM, CMSSM, BMSSM, ...)  
**Mu-chun Chen @ SUSY11 (THU)**
  - ▶ (SUSY-) GUTs e.g.: Buras, Nagai, Paradisi (2010);  
Girrbach et al. (2011) **A. de la Puente @ SUSY11 (SUN)**  
**W. Altmannshofer @ SUSY11 (THU)**
  - ▶ models with extra dimensions (UED, RS, ...)
  - ▶ models with extended Higgs sectors e.g.: Buras, Carlucci, Gori, Isidori (2010); Blankenburg, Isidori (2011)
  - ▶ models with a 4<sup>th</sup> generation e.g.: Buras et al. (2010); Rohrwild et al. (2009, 2010, 2011)
  - ▶ models with new gauge bosons  $W'$ ,  $Z'$
- Models featuring a **warped extra dimension (Randall-Sundrum)** offer a simultaneous, **geometrical solution to the hierarchy and flavor problems**
  - ▶ very different from SUSY  
Csaki, Falkowski, Weiler (2008);  
Casagrande, Goertz, Haisch, MN, Pfoh (2008);  
Blanke, Buras, Duling, Gori, Weiler (2008);  
Blanke, Buras, Duling, Gemmler, Gori (2008);  
Bauer, Casagrande, Haisch, MN (2009)

# Outline

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- Flavor dynamics in a warped extra dimension
- Hints for New Physics in B-meson mixing
- Hints for New Physics in B-meson decays
- Outlook

Unfortunately no time for:

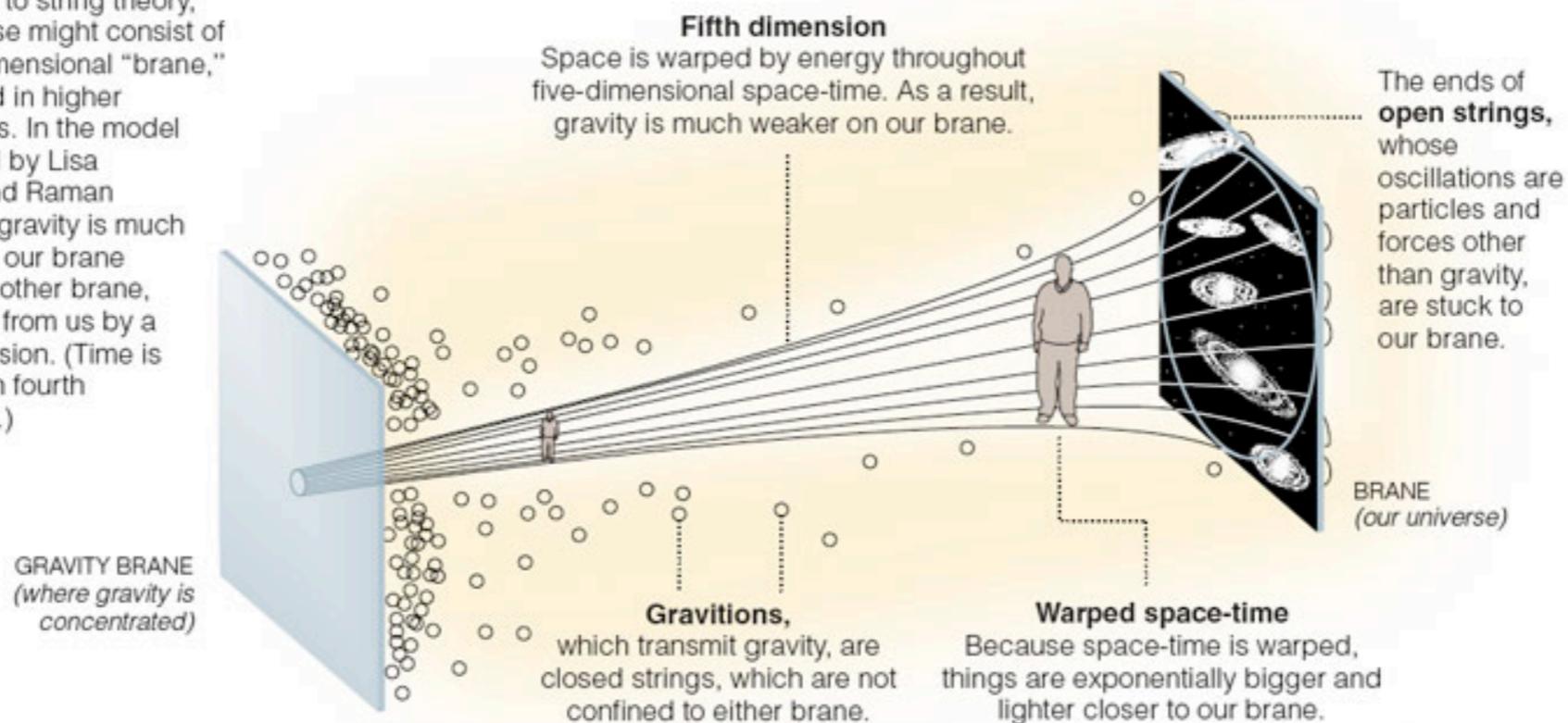


- Production of heavy flavors
- Spectroscopy and exotic states
- Detailed discussion of hadronic B-meson decays
- Detailed discussion of improved CKM measurements
- Charm decays and D-meson mixing ...

# Flavor dynamics in a warped extra dimension

## Island Universes in Warped Space-Time

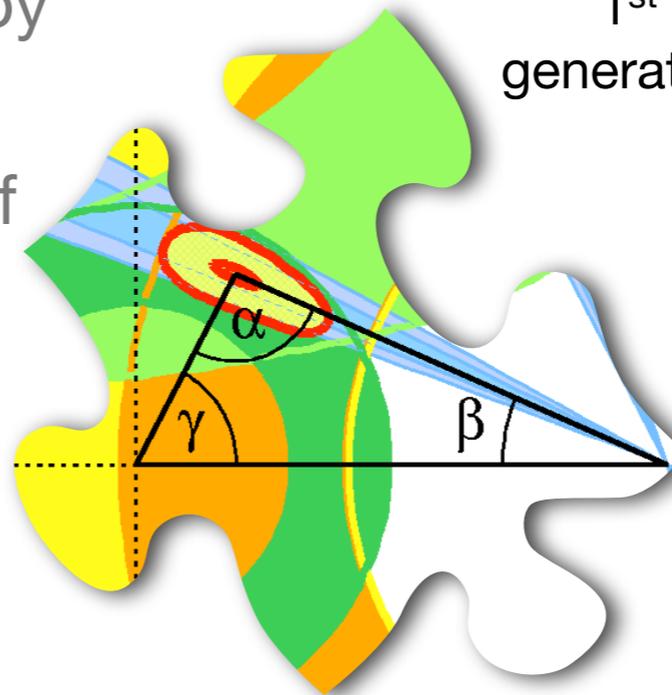
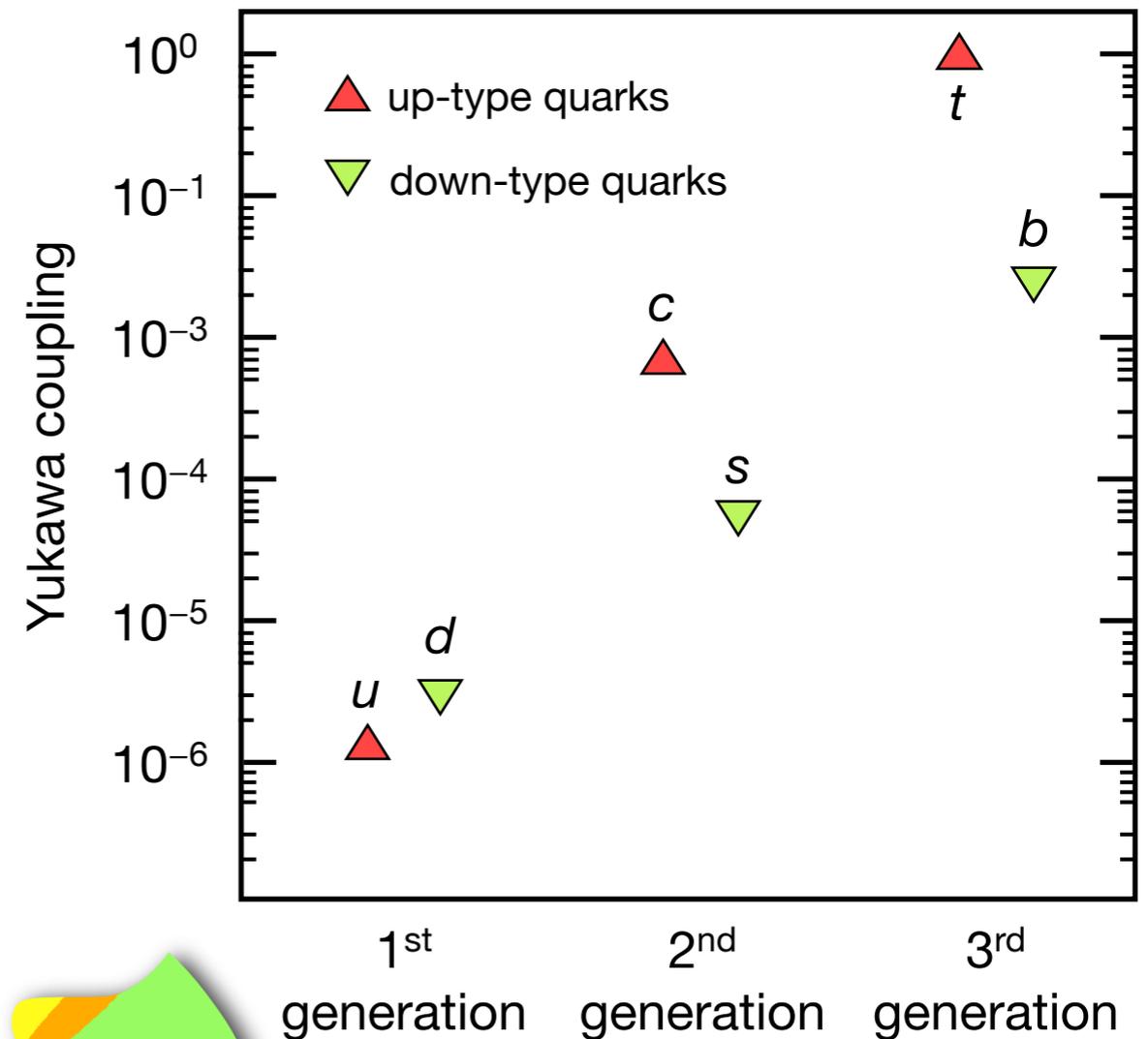
According to string theory, our universe might consist of a three-dimensional "brane," embedded in higher dimensions. In the model developed by Lisa Randall and Raman Sundrum, gravity is much weaker on our brane than on another brane, separated from us by a fifth dimension. (Time is the unseen fourth dimension.)



# What is the dynamics of flavor?

While SM **describes** flavor physics very accurately, it does not **explain** its mysteries:

- Why are there three generations in nature?
- Why does the spectrum of fermion masses cover so many orders of magnitude?
- Why is the mixing between different generations governed by small mixing angles?
- Why is the CP-violating phase of the CKM matrix unsuppressed?



# Flavor structure in RS models

Randall, Sundrum (1999)

ultraviolet (UV) brane

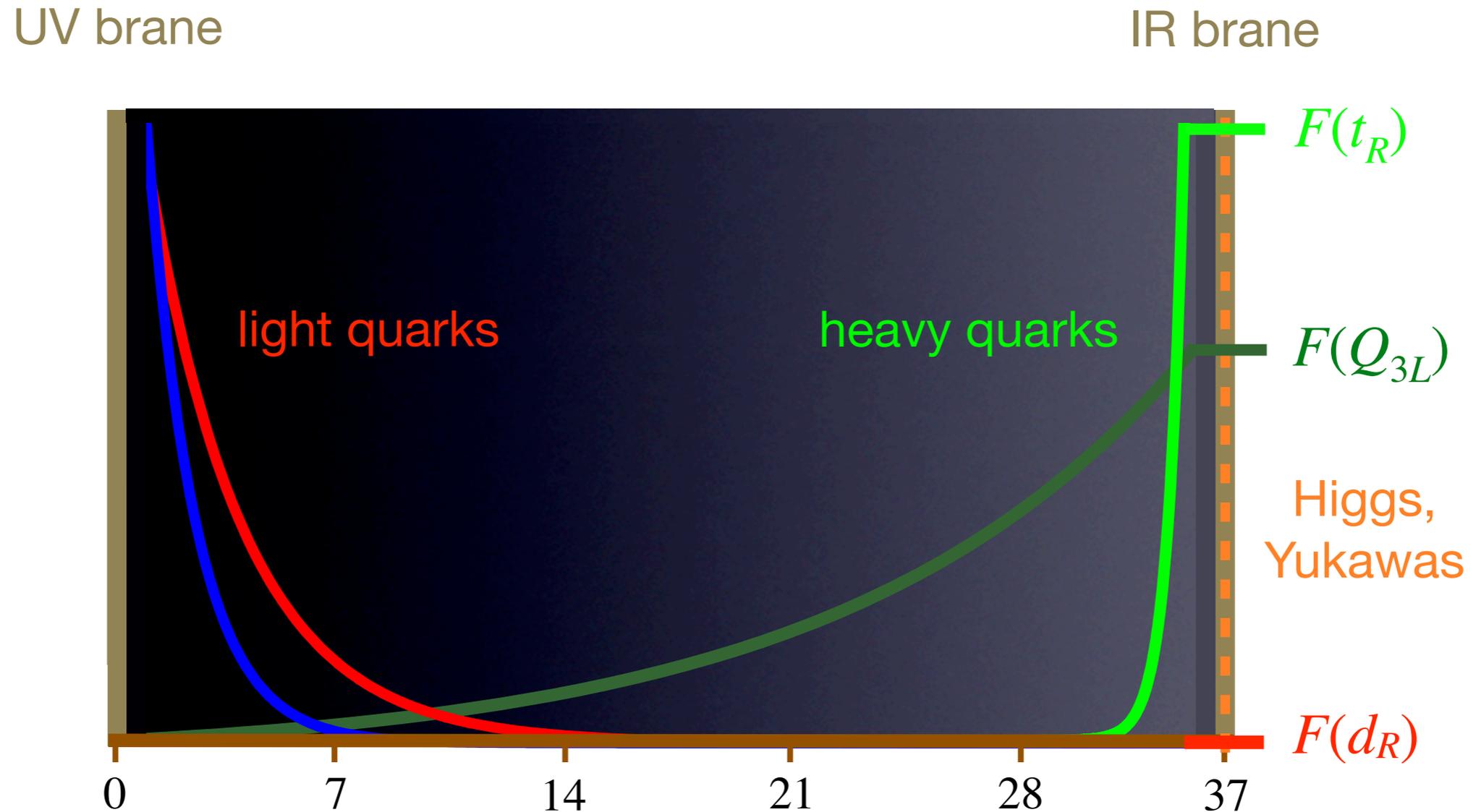
$$ds^2 = \left(\frac{R}{z}\right)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$$

infrared (IR) brane

$R$   $z$   $R'$

- Solution to gauge hierarchy problem via gravitational redshift
- AdS/CFT calculable strong electroweak-symmetry breaking: holographic technicolor, composite Higgs
- Unification possible due to logarithmic running of couplings

# Flavor structure in RS models



Localization of fermions in extra dimension depends exponentially on  **$O(1)$  parameters** related to the five-dimensional **bulk masses**. Overlaps  $F(Q_L)$ ,  $F(q_R)$  with IR-localized Higgs sector and Yukawa couplings are **exponentially small** for light quarks, while  $O(1)$  for top quark

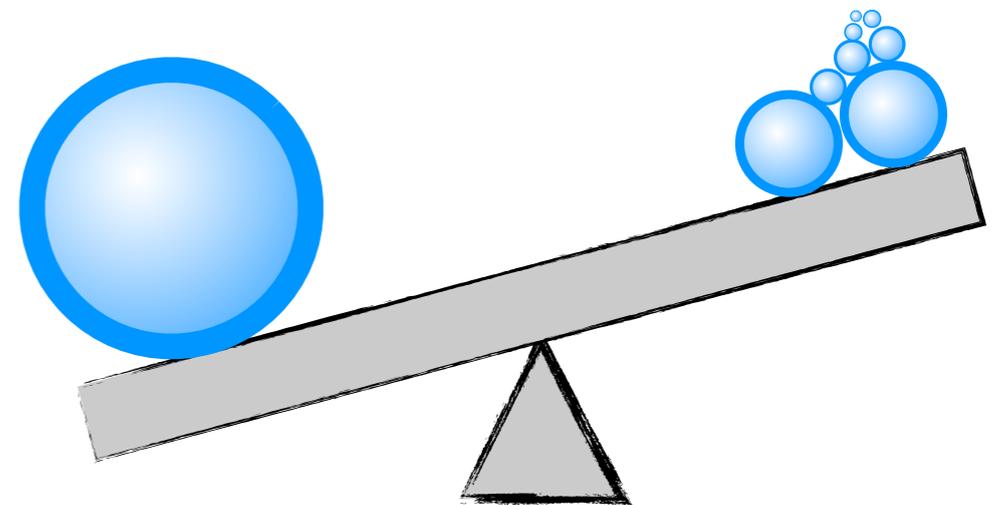
# Hierarchies of quark masses and CKM angles

SM mass matrices can be written as: [Huber \(2003\)](#)

$$m_q^{\text{SM}} = \frac{v}{\sqrt{2}} \text{diag} [F(Q_i)] \mathbf{Y}_q \text{diag} [F(q_i)] = \begin{pmatrix} \cdot & \cdot & \blacksquare \\ \cdot & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix}$$

where  $\mathbf{Y}_q$  with  $q = u, d$  are structureless, complex Yukawa matrices with  $O(1)$  entries, and  $F(Q_i) \ll F(Q_j)$ ,  $F(q_i) \ll F(q_j)$  for  $i < j$

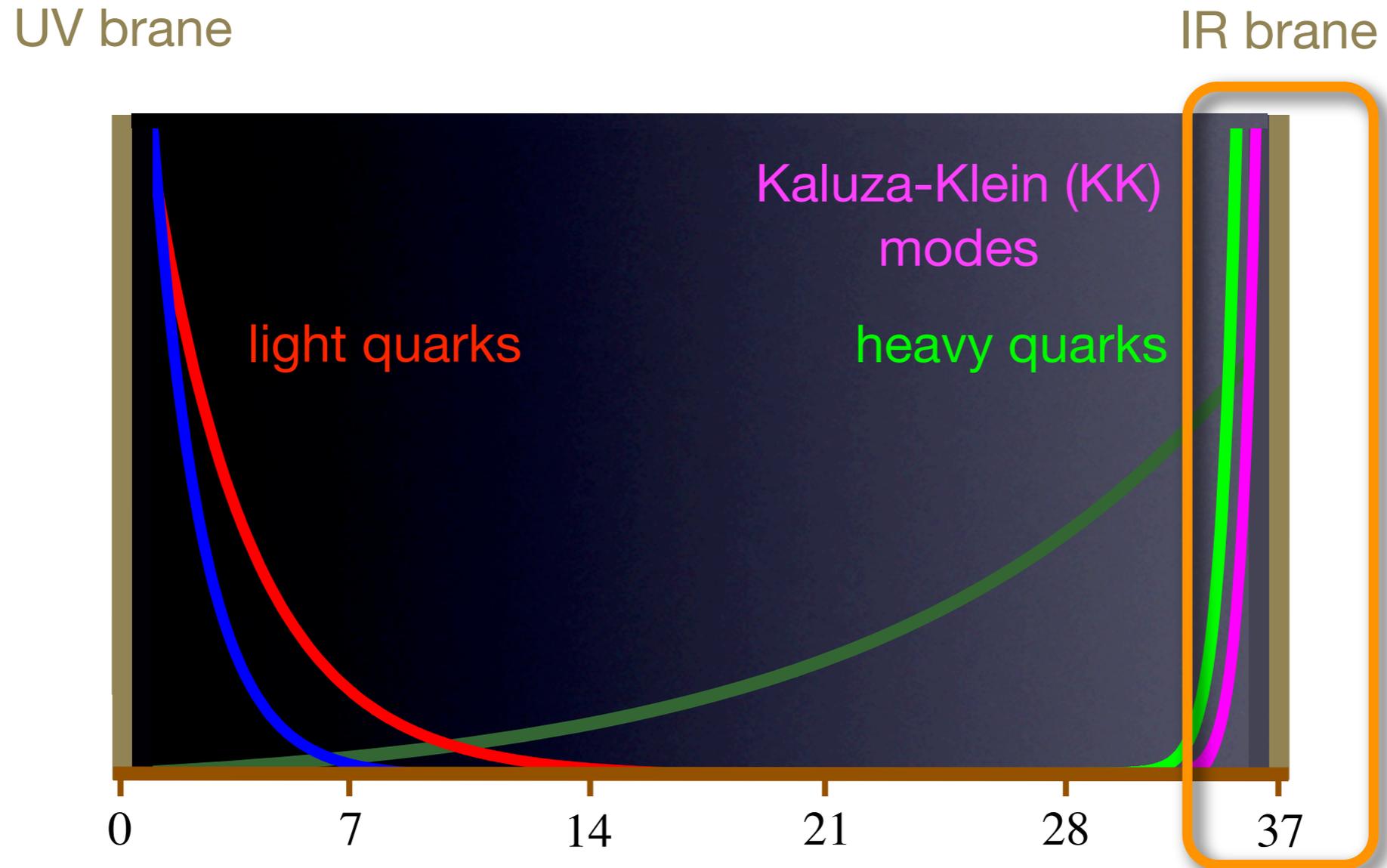
- In analogy to seesaw mechanism, matrices of this form give rise to hierarchical mass eigenvalues and mixing matrices
- Hierarchies can be adjusted by  $O(1)$  variations of bulk mass parameters
- Yet the CKM phase is predicted to be  $O(1)$



**Warped-space Froggatt-Nielsen mechanism!**

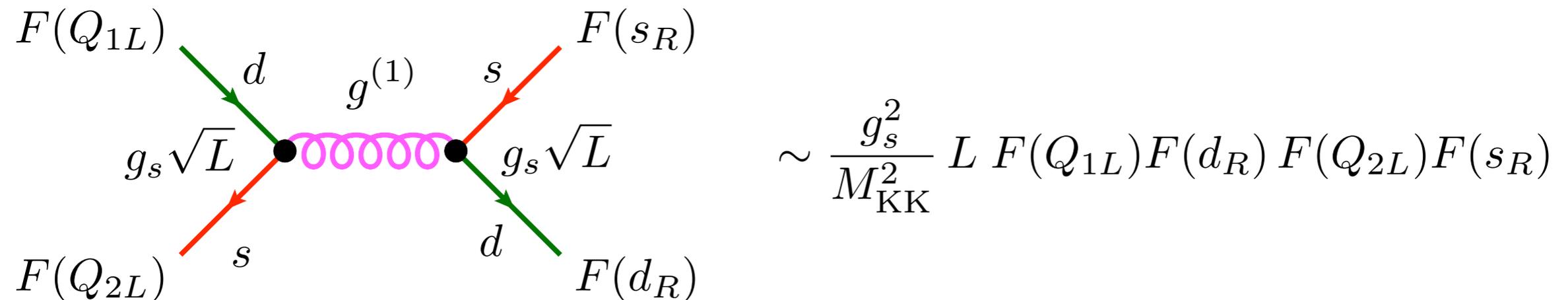
[Casagrande et al. \(2008\)](#); [Blanke et al. \(2008\)](#)

# Flavor structure in RS models



Kaluza-Klein (KK) excitations of SM particles live close to the IR brane

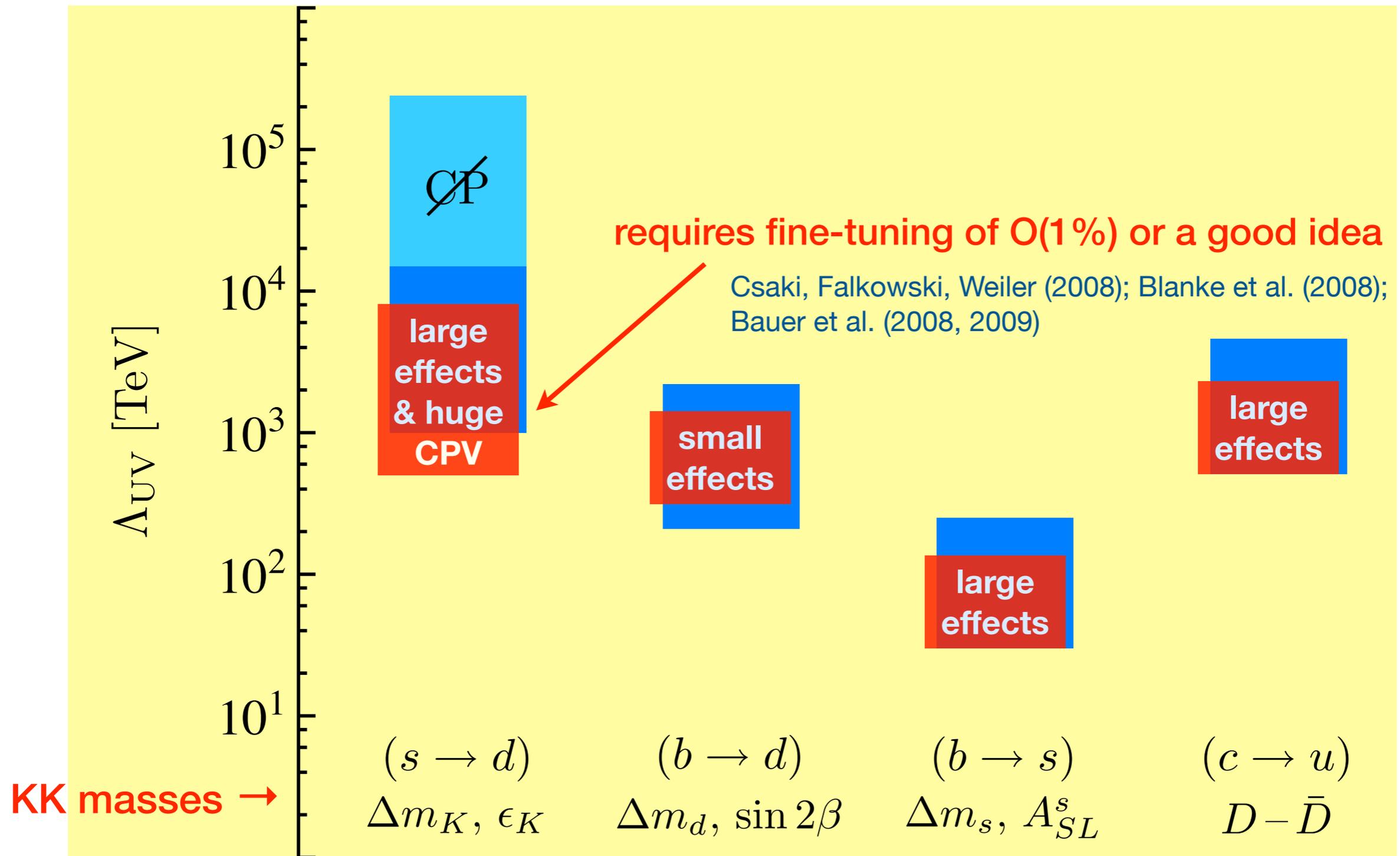
# RS-GIM protection of FCNCs



- Quark FCNCs are induced at tree-level through virtual exchange of KK gauge bosons (including KK gluons!) [Huber \(2003\)](#); [Burdman \(2003\)](#); [Agashe et al. \(2004\)](#); [Casagrande et al. \(2008\)](#)
- Resulting FCNC couplings depend on same exponentially small overlaps  $F(Q_L)$ ,  $F(q_R)$  that generate fermion masses
- FCNCs involving quarks other than top are strongly suppressed (true for all induced FCNC couplings) [Agashe et al. \(2004\)](#)

**This mechanism suffices to suppress all but one of the dangerous FCNC couplings!**

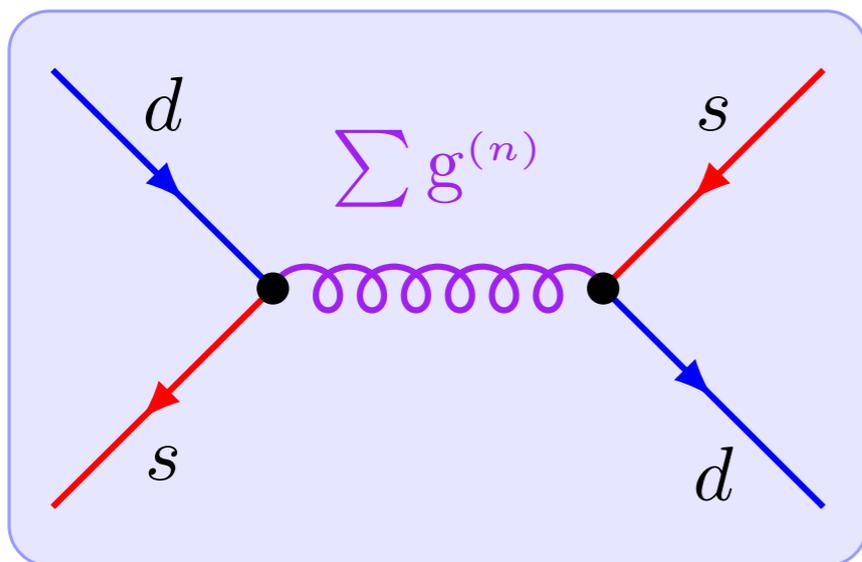
# RS-GIM protection of FCNCs



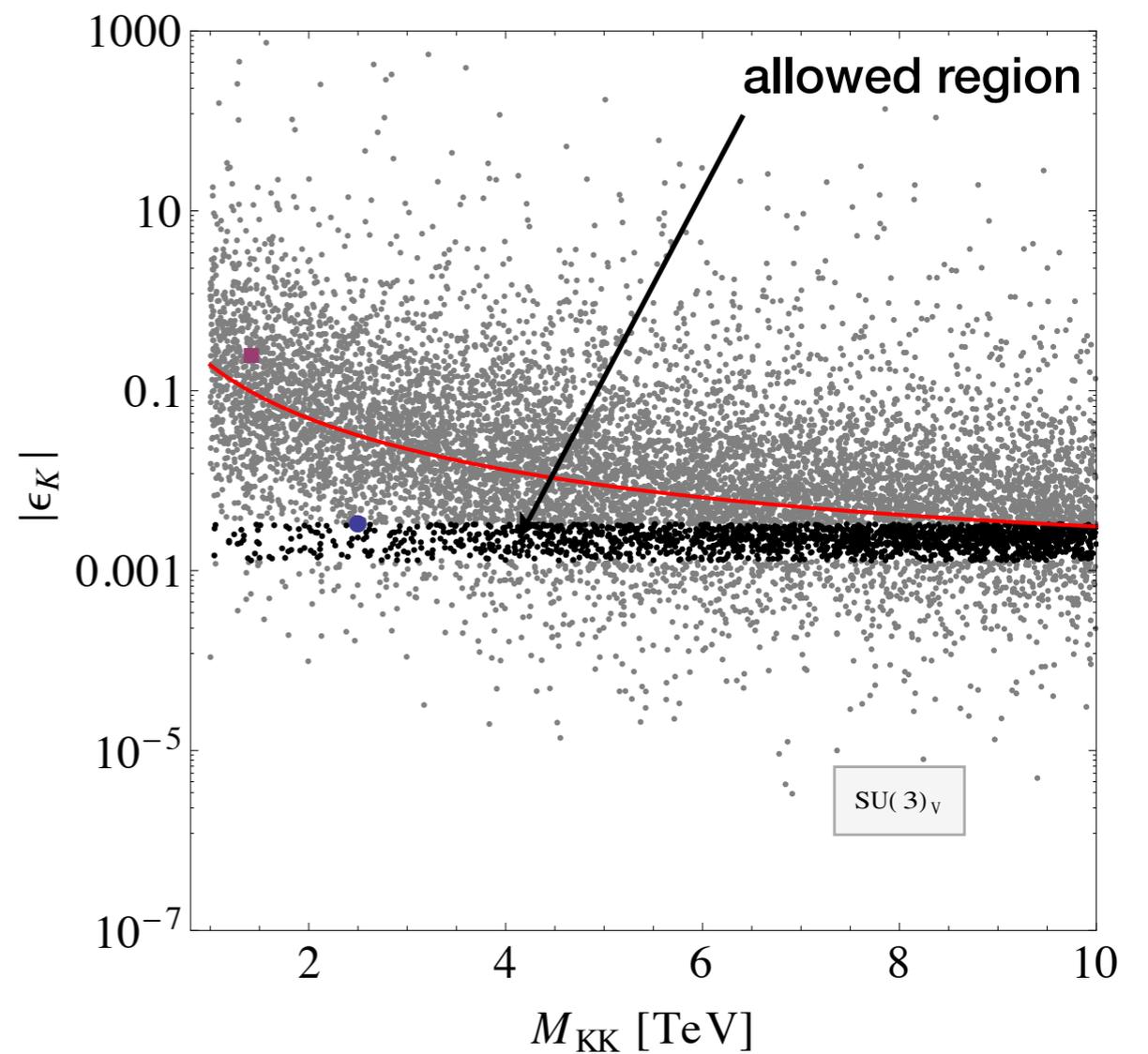
RS-GIM protection with KK masses of order few TeV

# The RS flavor problem: CPV in kaon mixing

Flavor-violating couplings from KK gluon exchange induce effective 4-fermion operators of mixed chirality, whose contributions to  $K-\bar{K}$  mixing are enhanced by two orders of magnitude (chiral enhancement + RG evolution) with respect to the left-handed current-current operators of the SM:



This leads to very large contributions to  $\epsilon_K$ :



(first KK gluon has mass  $2.45 M_{KK}$ )

Csaki, Falkowski, Weiler (2008); Blanke et al. (2008); Bauer et al. (2008, 2009)

# A solution to the RS flavor problem

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An elegant solution is to extend the strong gauge group to

$$SU(3)_{\text{doublet}} \otimes SU(3)_{\text{singlet}}$$

Bauer, Malm, MN (2011)

and break it to  $SU(3)_V$  using boundary conditions on the UV and IR branes:

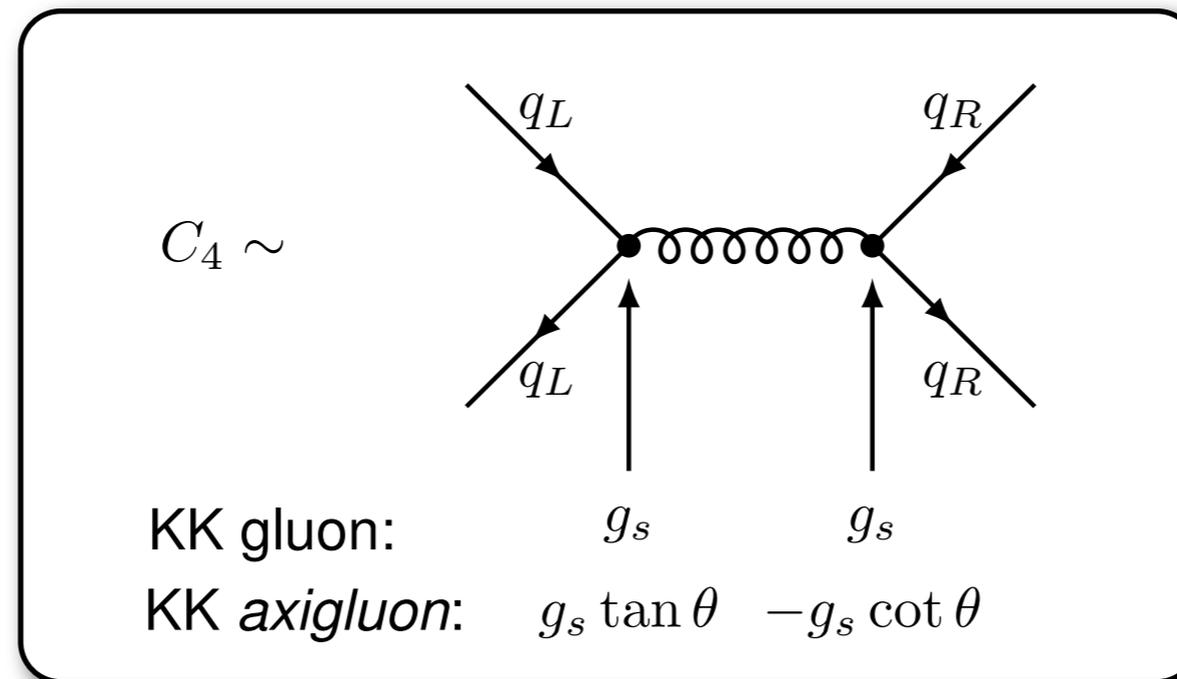
$$\begin{aligned} \mathcal{L}_{\text{int}} &\ni g_D \bar{Q} G_{\mu}^D \gamma^{\mu} Q + g_S \bar{q} G_{\mu}^S \gamma^{\mu} q \\ &= g_s (\bar{Q} g_{\mu} \gamma^{\mu} Q + \bar{q} g_{\mu} \gamma^{\mu} q) \\ &\quad + g_s (\tan \theta \bar{Q} A_{\mu} \gamma^{\mu} Q - \cot \theta \bar{q} A_{\mu} \gamma^{\mu} q) \end{aligned}$$

The gluon field  $g_{\mu} = G_{\mu}^D \cos \theta + G_{\mu}^S \sin \theta$  with  $\tan \theta = g_D / g_S$  has a massless zero mode (the SM gluon), while the **pseudo-axial gluon**  $A_{\mu} = G_{\mu}^D \sin \theta - G_{\mu}^S \cos \theta$  only gives rise to massive KK modes

# A solution to the RS flavor problem

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Since the left/right-handed SM quarks are the zero modes of SU(2) doublet/singlet fields, we achieve opposite-sign couplings for mixed-chirality 4-quark operators for any value of  $\theta$ :



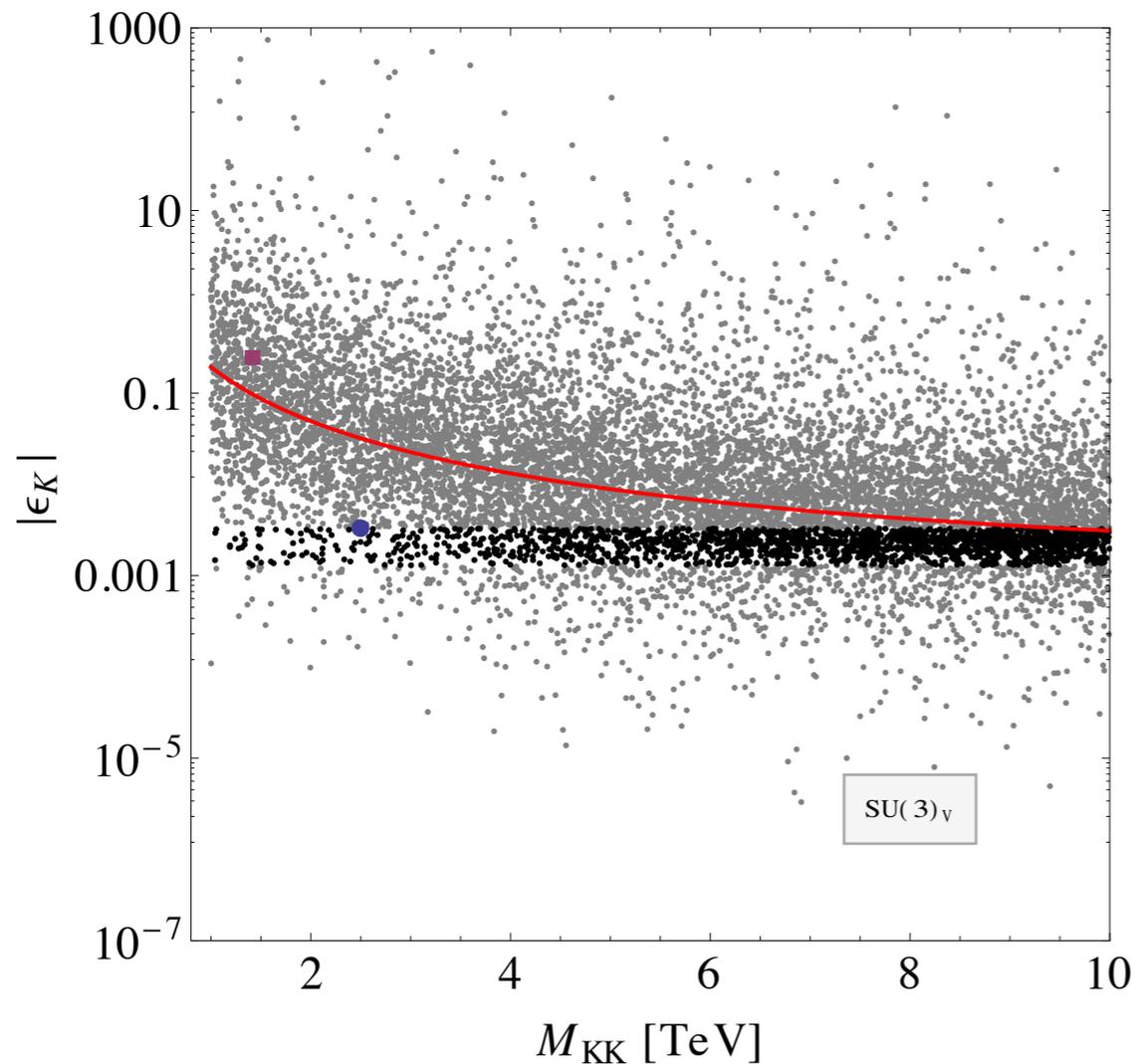
Martin Bauer @ SUSY11  
(THU)

**These contributions from the two KK towers cancel exactly  
for a large set of boundary conditions!**

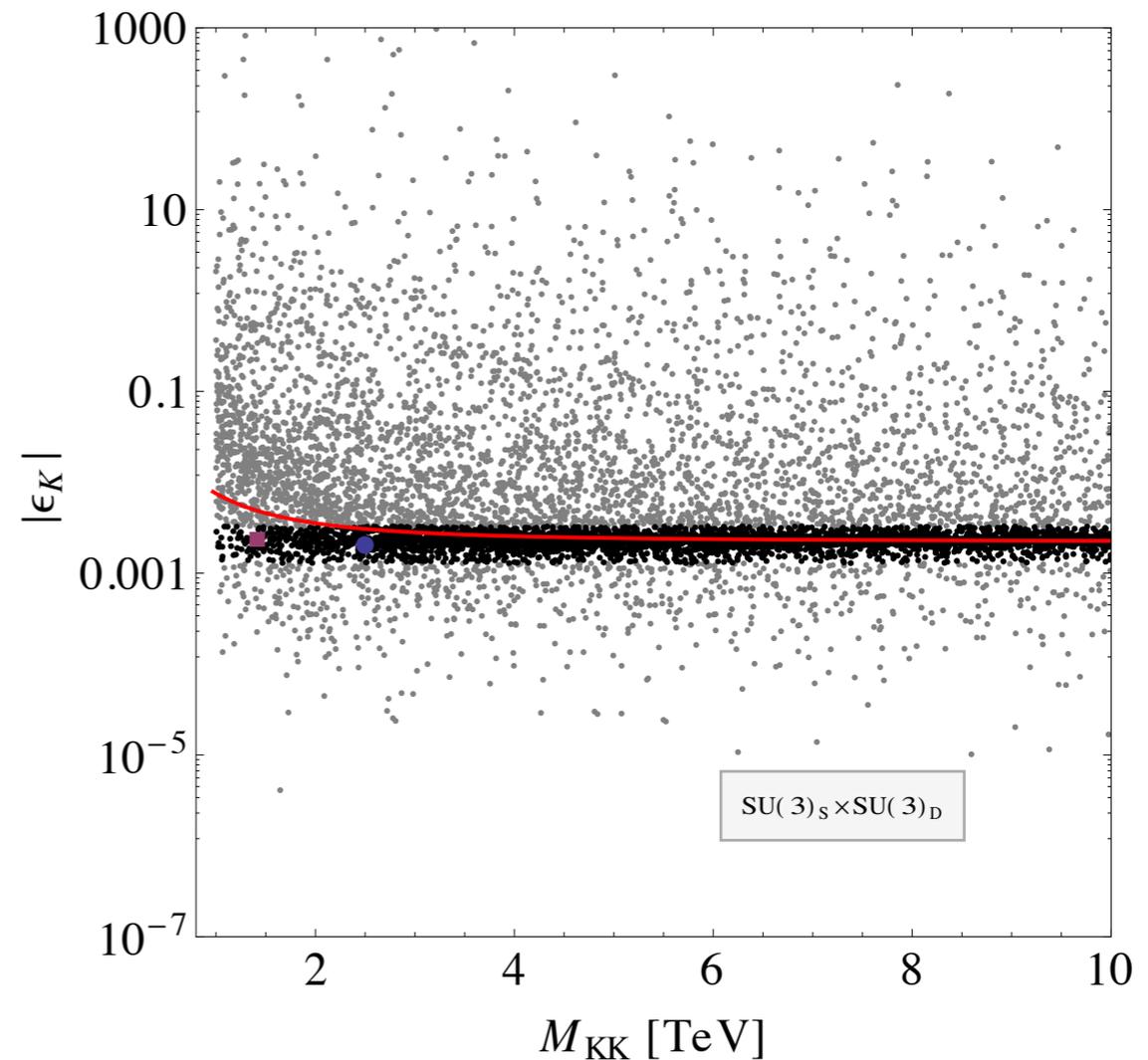
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Bauer, Malm, MN (2011)



(first KK gluon has mass  $2.45 M_{\text{KK}}$ )

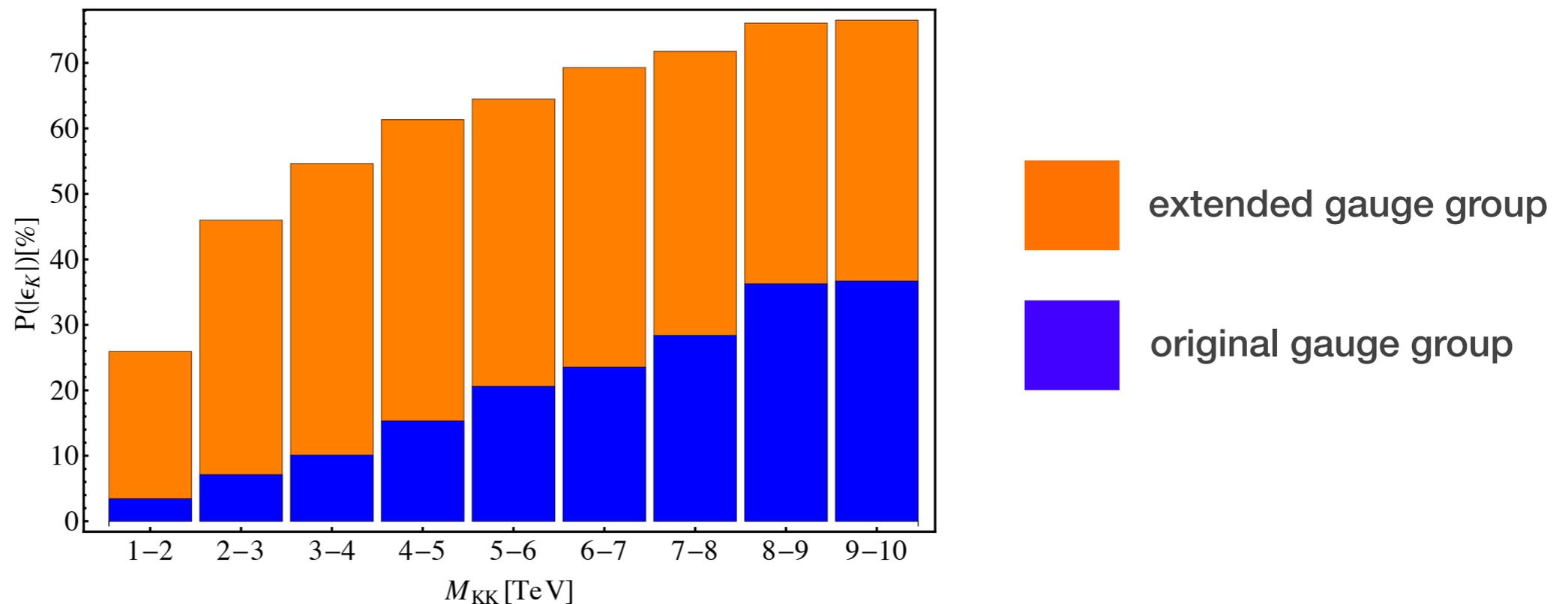


(first KK axigluon can have mass  $0.85 M_{\text{KK}}$ )

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Since the left/right-handed SM quarks are the zero modes of SU(2) doublet/singlet fields, we achieve opposite-sign couplings for mixed-chirality 4-quark operators for any value of  $\theta$ :

Bauer, Malm, MN (2011)

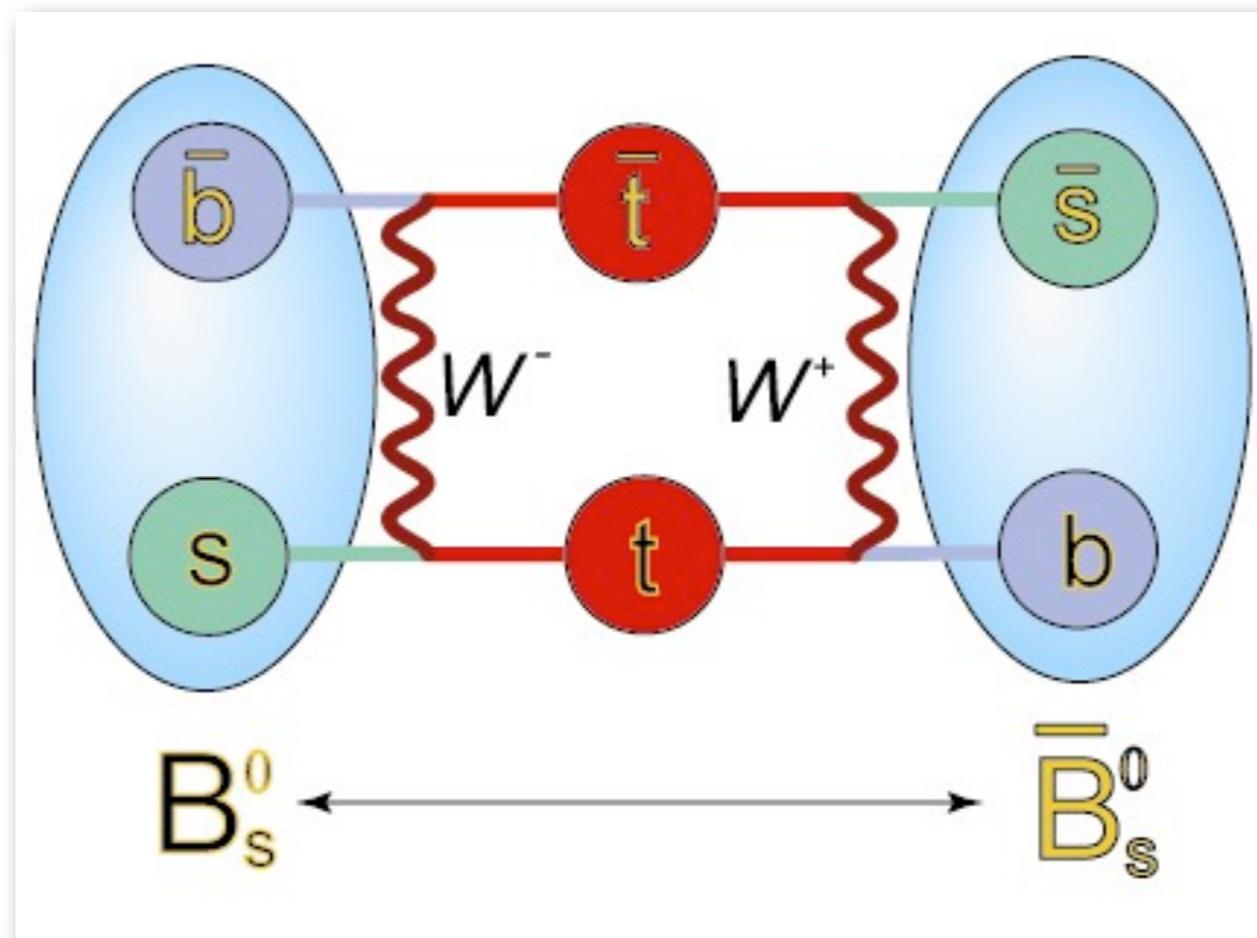


Remarkably, for a large class of boundary conditions this mechanism provides an explanation of the **anomalously large forward-backward asymmetry** in top-quark pair production seen at the Tevatron (via s-channel pseudo-axigluon exchange), without being in conflict with LHC dijet bounds!

Martin Bauer @ SUSY11  
(THU)

# Hints for New Physics in B-meson mixing

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# Basic formulae

Schrödinger equation:

$$i \frac{d}{dt} \begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \left( M^q - \frac{i}{2} \Gamma^q \right) \begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$

Three observables:

$$\phi_q = \arg(-M_{12}^q / \Gamma_{12}^q) \quad \text{CPV phase}$$

$$\Delta M_q = M_H^q - M_L^q = 2 |M_{12}^q| \quad \text{oscillation frequency (short-distance)}$$

$$\Delta \Gamma_q = \Gamma_L^q - \Gamma_H^q = 2 |\Gamma_{12}^q| \cos \phi_q \quad \text{width difference (common final states)}$$

Flavor-specific (e.g. semileptonic) asymmetries, assuming no CPV in the decay amplitudes:

$$a_{\text{fs}}^q = a_{\text{SL}}^q = \text{Im} \frac{\Gamma_{12}^q}{M_{12}^q} = \frac{|\Gamma_{12}^q|}{|M_{12}^q|} \sin \phi_q = \frac{\Delta \Gamma_q}{\Delta M_q} \tan \phi_q$$

Parametrization of New Physics effects (assuming NP only in  $M_{12}^q$ ):

$$\frac{M_{12}^q}{M_{12}^{\text{SM},q}} = \Delta_q = |\Delta_q| e^{i\phi_q^\Delta} = 1 + h_q e^{i2\sigma_q}$$

# CP-violating observables

Mixing-induced, time-dependent CP asymmetries in decays to CP eigenstates:

$$S_{\psi K} = \sin(2\beta + \phi_d^\Delta) \qquad S_{\psi\phi} = \sin(2\beta_s - \phi_s^\Delta)$$

Semileptonic asymmetry measured at B factories:  $a_{\text{SL}}^d$

Flavor-specific asymmetry in tree-level  $B_s^0 \rightarrow \mu^+ D_s^- X$  decays (D0):  $a_{\text{fs}}^s = a_{\text{SL}}^s$

Like-sign dimuon charge asymmetry (D0):

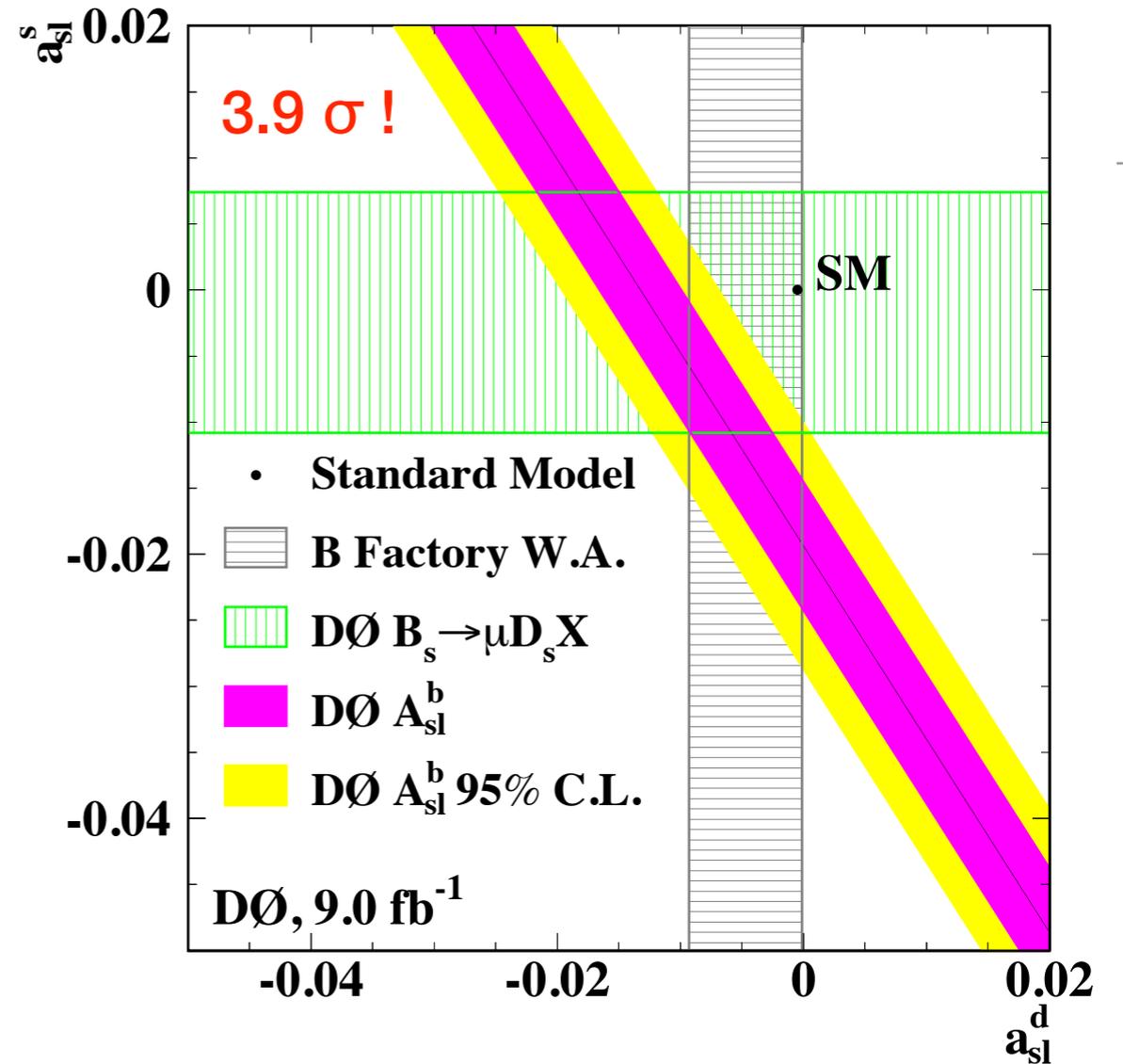
$$A_{\text{sl}}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = C_d a_{\text{SL}}^d + (1 - C_d) a_{\text{SL}}^s; \quad C_d = 0.594 \pm 0.022$$

determined from data

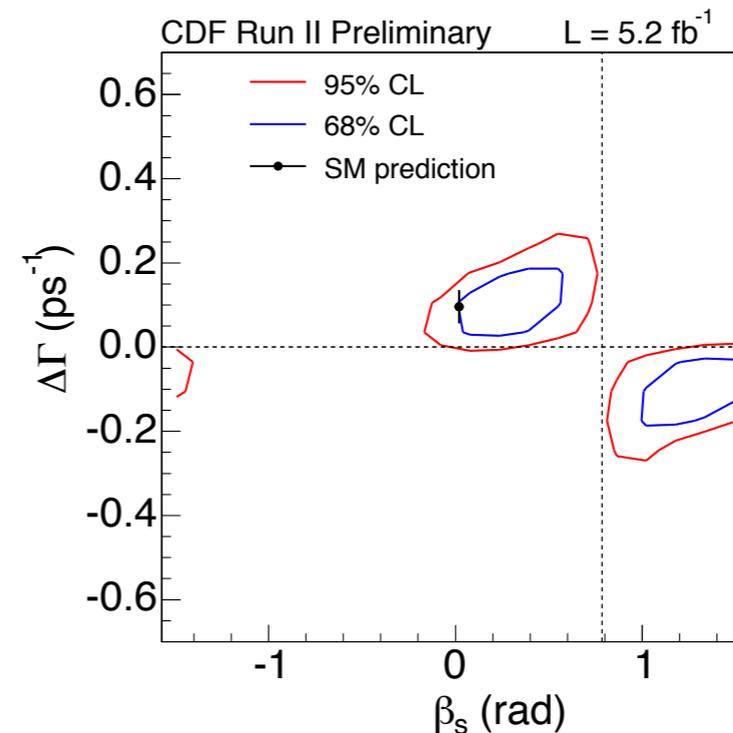
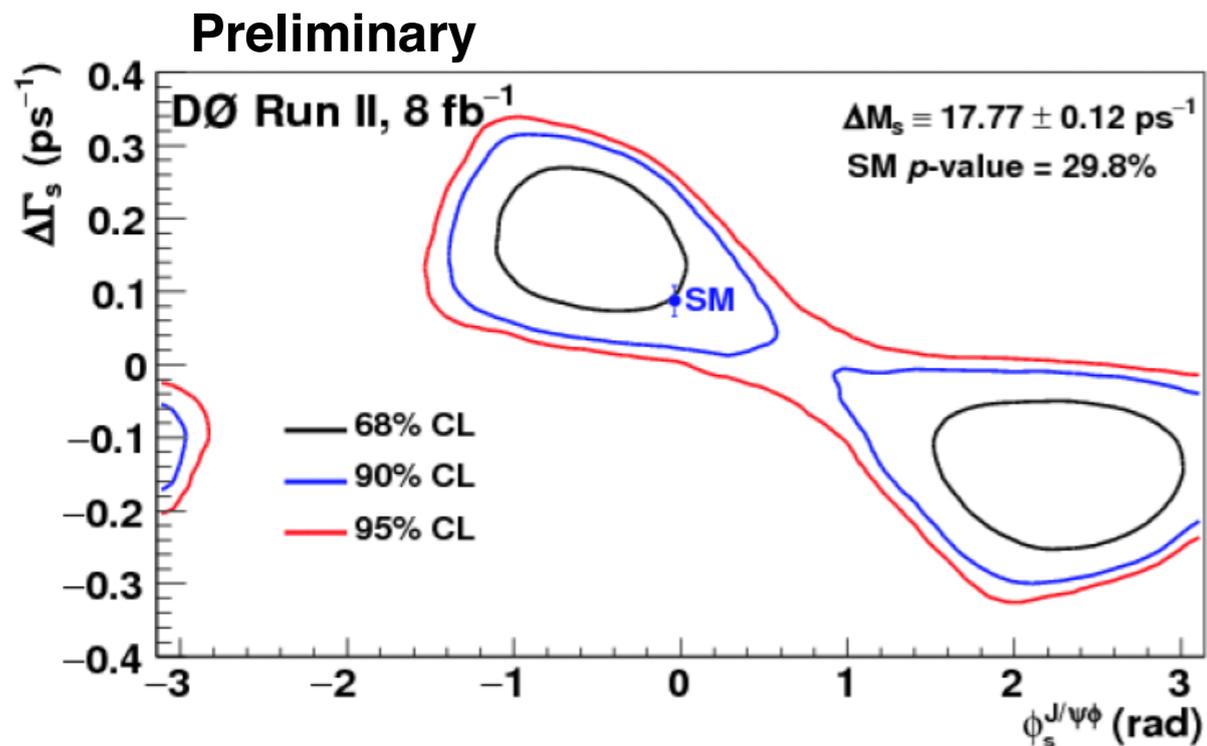
# Tevatron data

Like-sign dimuon charge asymmetry (DØ):

- not an easy measurement
- if taken at face value, a rather compelling hint of New Physics!

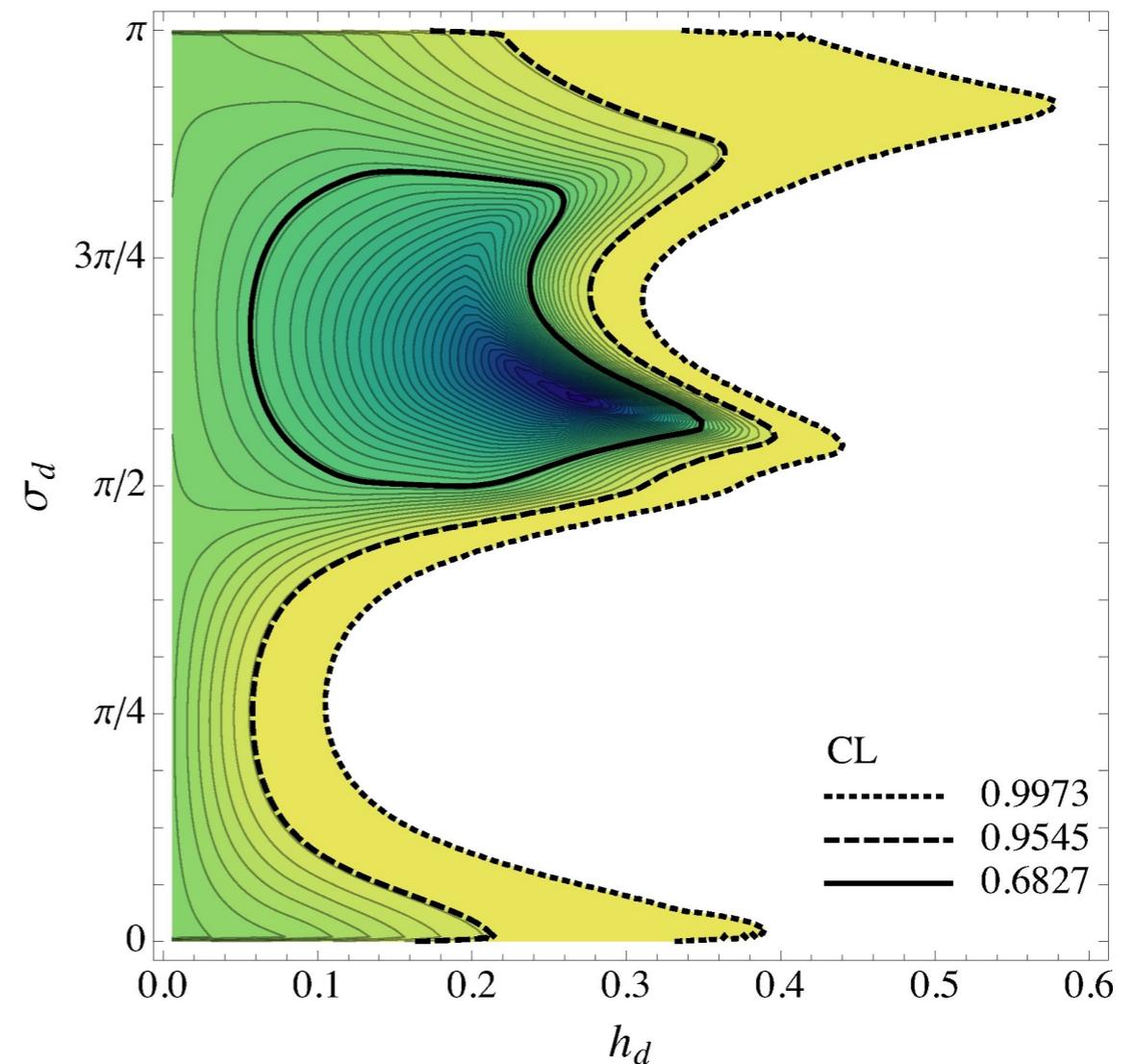
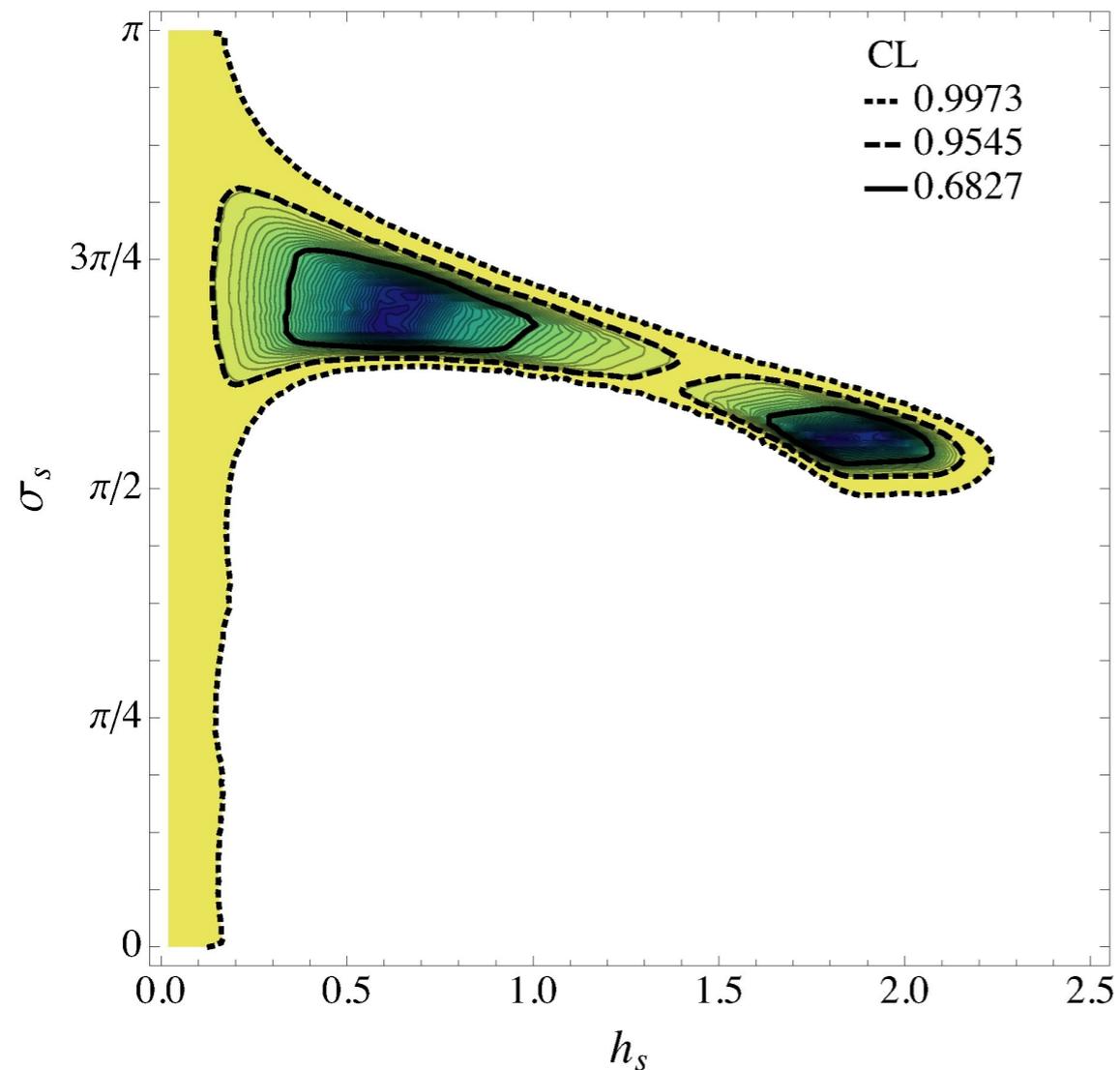


Mixing-induced CP asymmetry ( $B_s$ ):



# Theoretical analyses (prior to $D\bar{0}$ update)

Constraints on New Physics parameters  $(h_d, \sigma_d)$  and  $(h_s, \sigma_s)$ : [Ligeti, Papucci, Perez, Zupan \(2010\)](#)

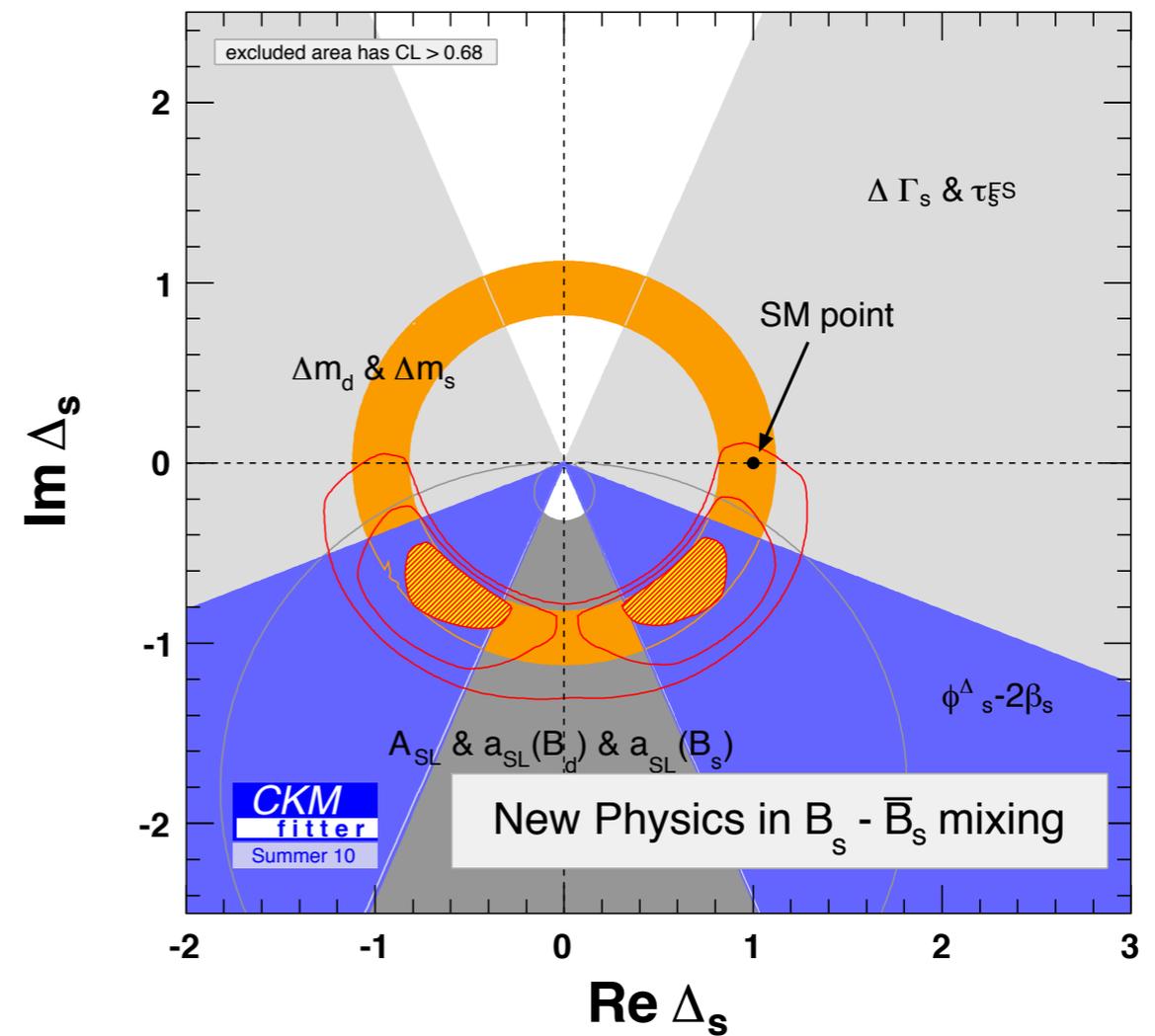
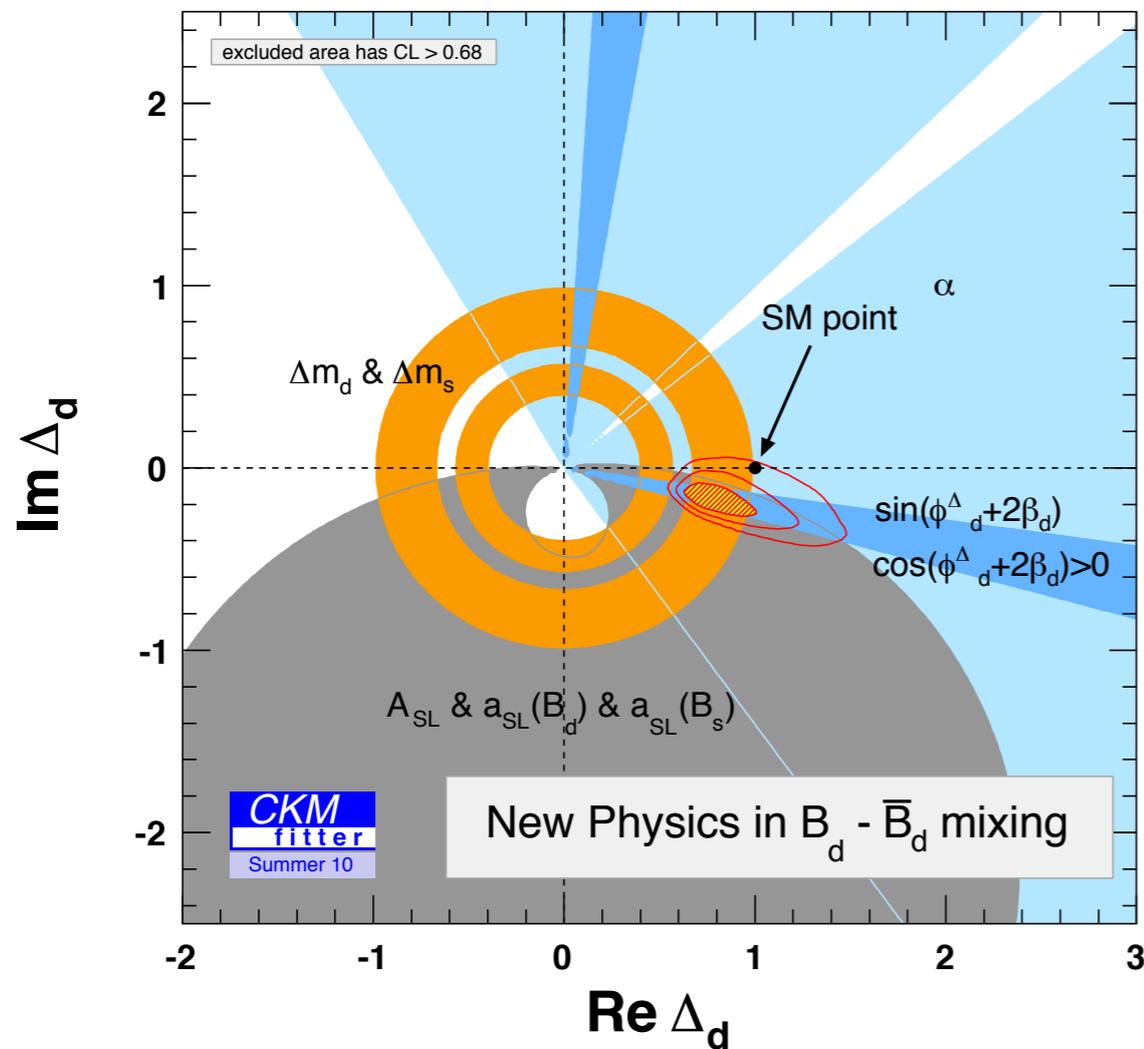


- SM ( $h_d=h_s=0$ ) disfavored at  $<3\sigma$  in  $B_s$  mixing and  $<2\sigma$  in  $B_d$  mixing
- case  $h_d=h_s$  and  $\sigma_d=\sigma_s$  (e.g., minimal flavor violation models) **strongly disfavored**

# Theoretical analyses (prior to $D\bar{D}$ update)

Constraints on New Physics parameters  $\Delta_d$  and  $\Delta_s$ :

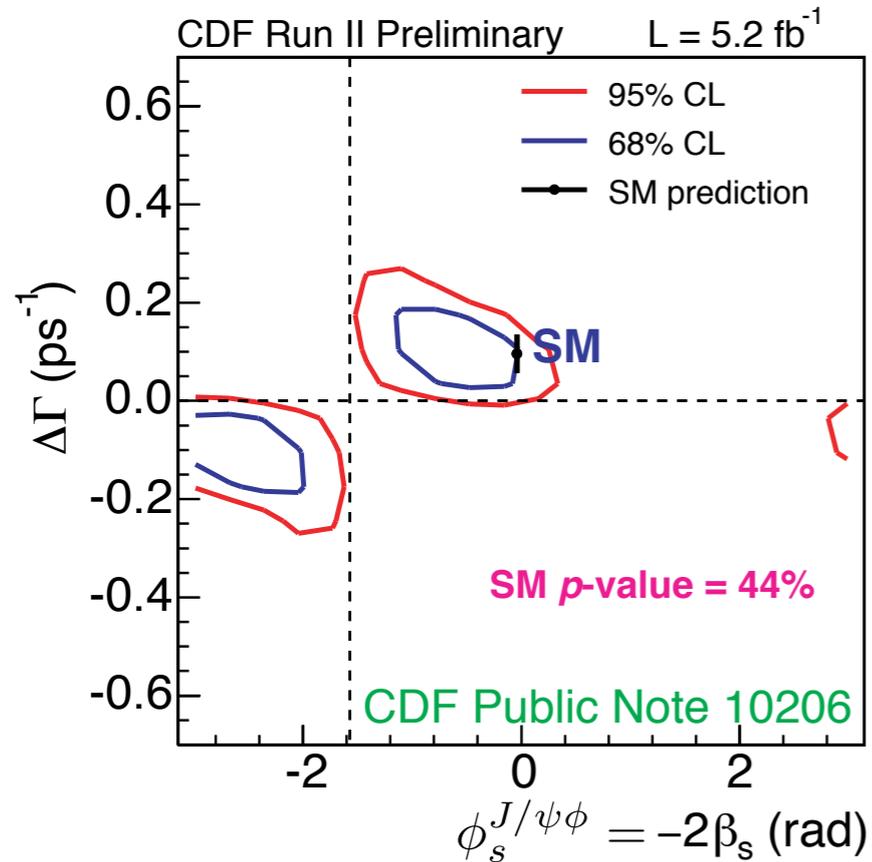
Lenz, Nierste + CKMfitter (2010)



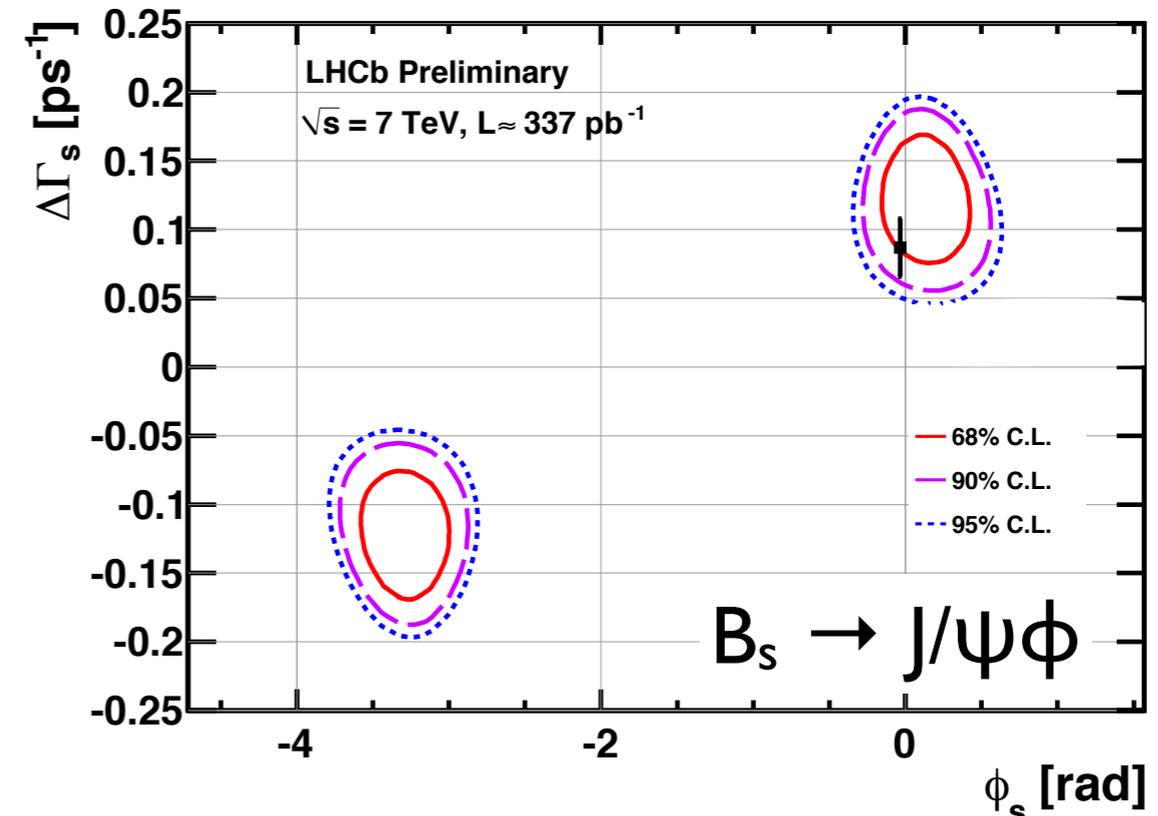
- SM ( $\Delta_d = \Delta_s = 1$ ) disfavored at  $3.6\sigma$
- no indication of New Physics in  $K - \bar{K}$  mixing
- minimal flavor violation ( $\Delta_d = \Delta_s$  real) disfavored at  $3.7\sigma$  (generalized MVF is still ok)

# The drama of Lepton-Photon 2011

Tevatron results for  $\Phi_s$



LHCb result for  $\Phi_s$  at LP11



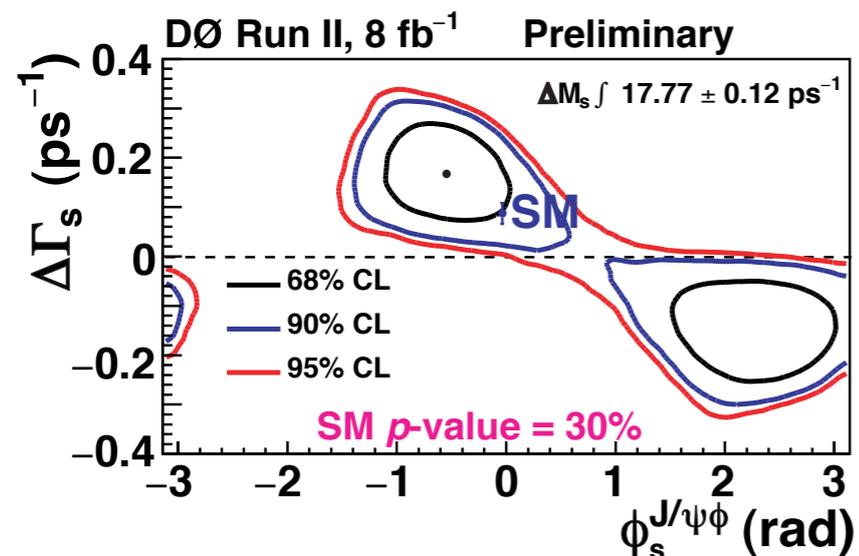
$$\phi_s = 0.13 \pm 0.18 \text{ (stat)} \pm 0.07 \text{ (syst)}$$

$$\Delta\Gamma_s = 0.123 \pm 0.029 \text{ (stat)} \pm 0.008 \text{ (syst)} \text{ ps}^{-1}$$

When combined with  $B_s \rightarrow J/\psi f_0$ :

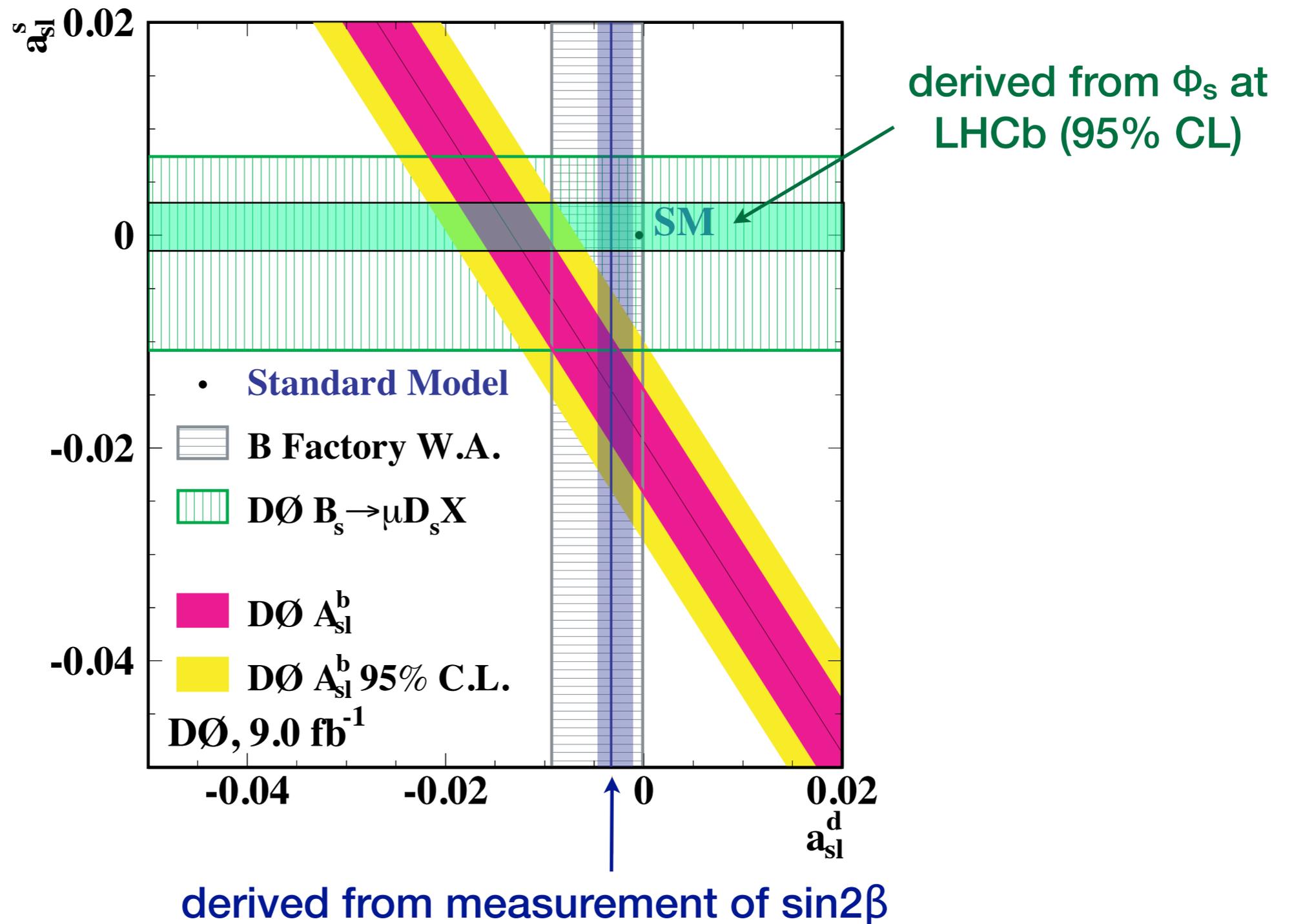
$$\phi_s = 0.03 \pm 0.16 \pm 0.07 \text{ rad}$$

$$\text{SM: } \phi_s = -0.004$$



# The drama of Lepton-Photon 2011

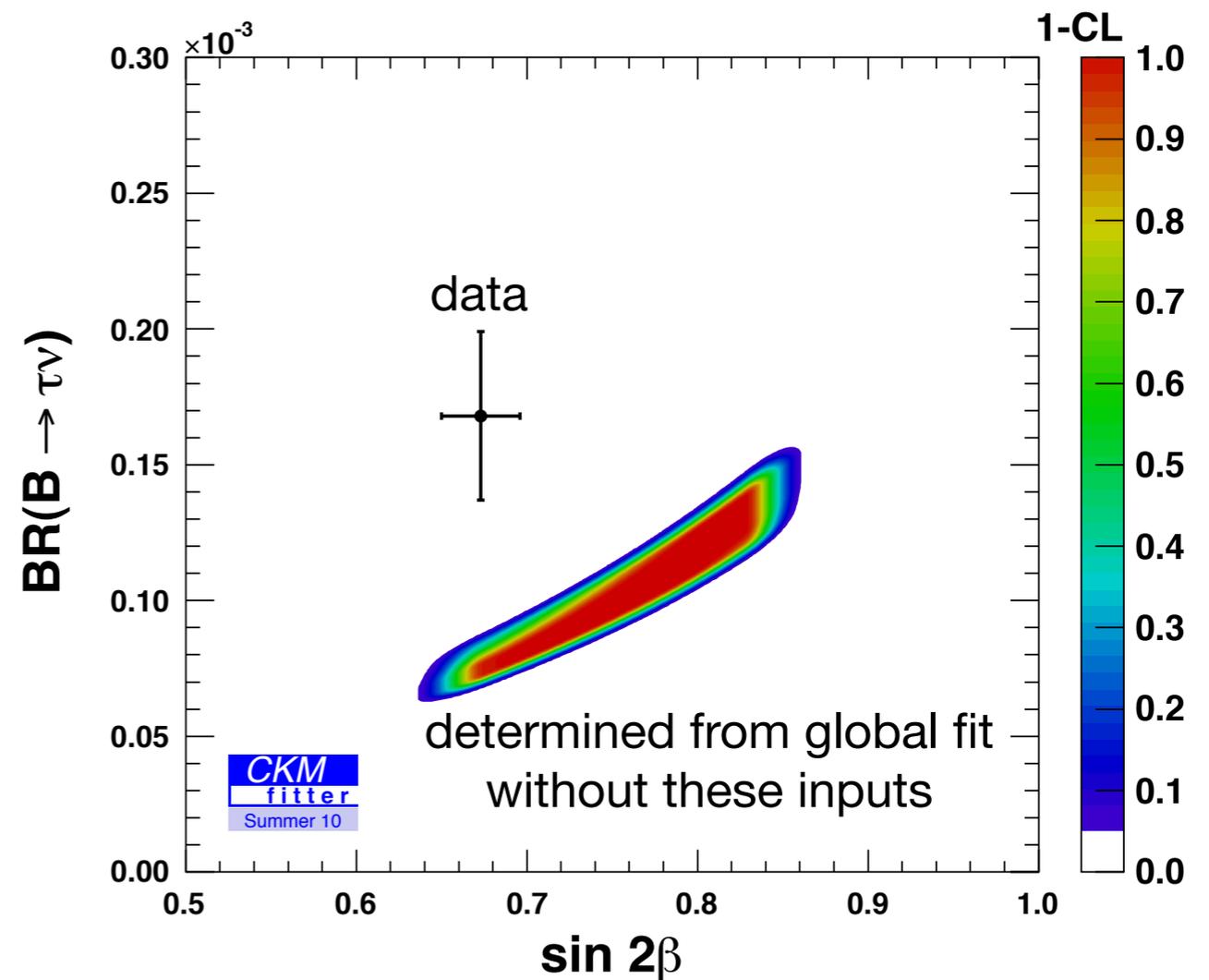
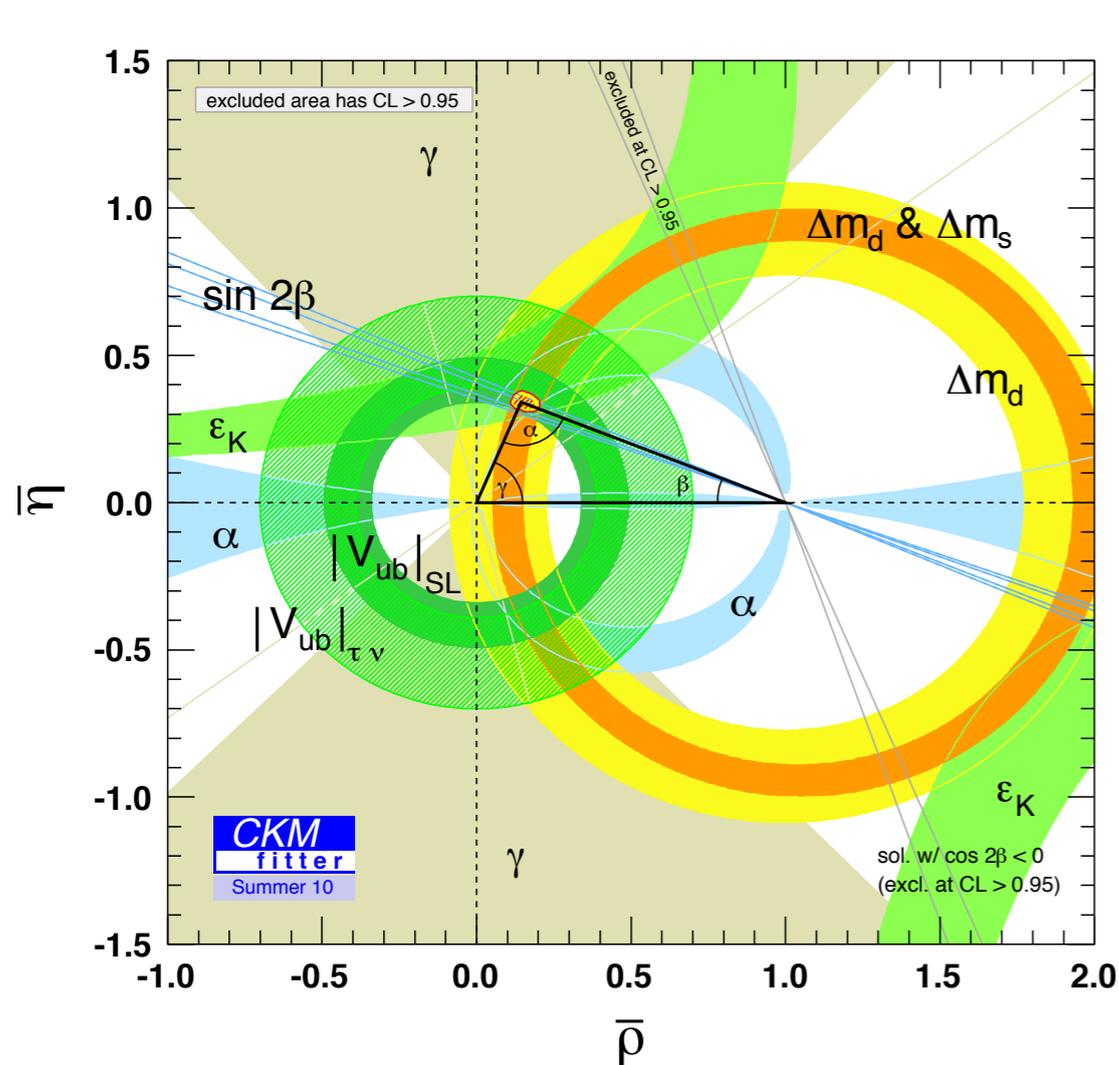
Implication for the interpretation of the  $D\bar{0}$  dimuon asymmetry:



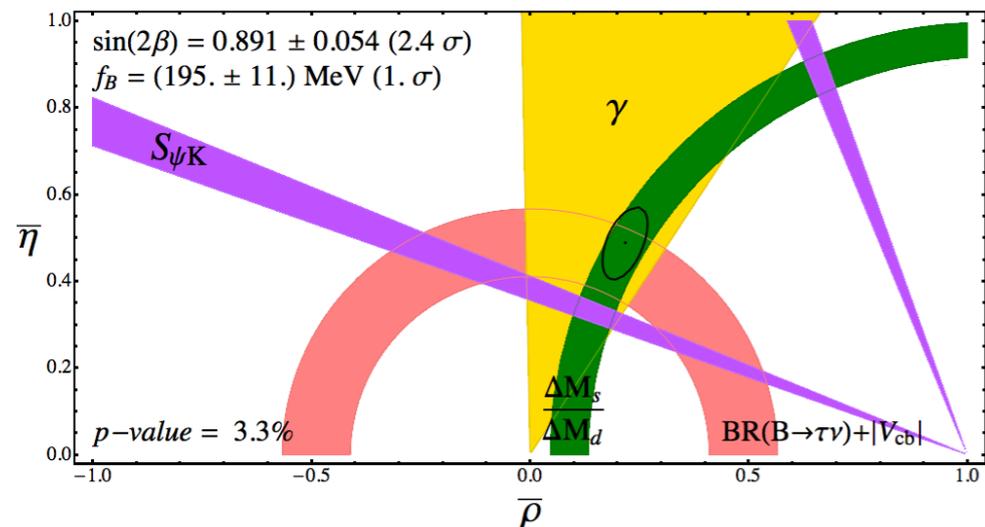
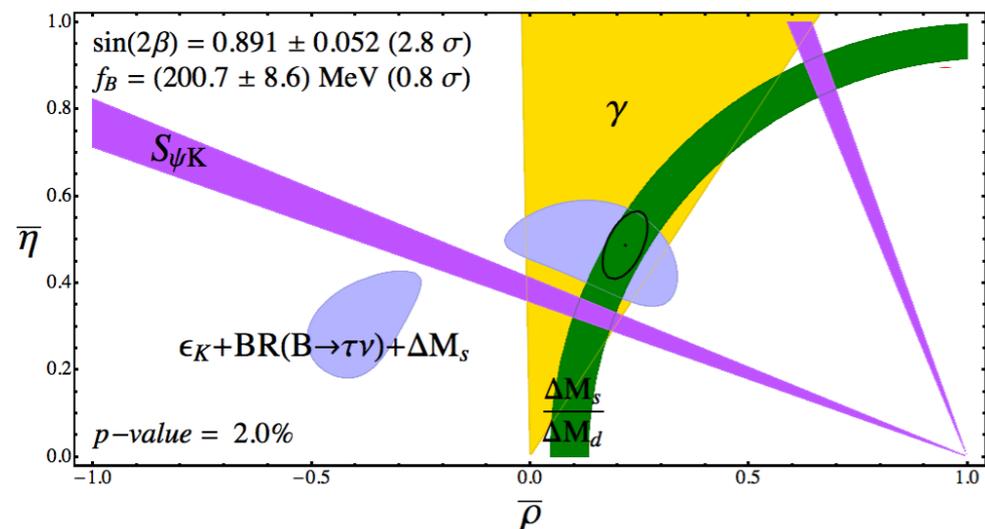
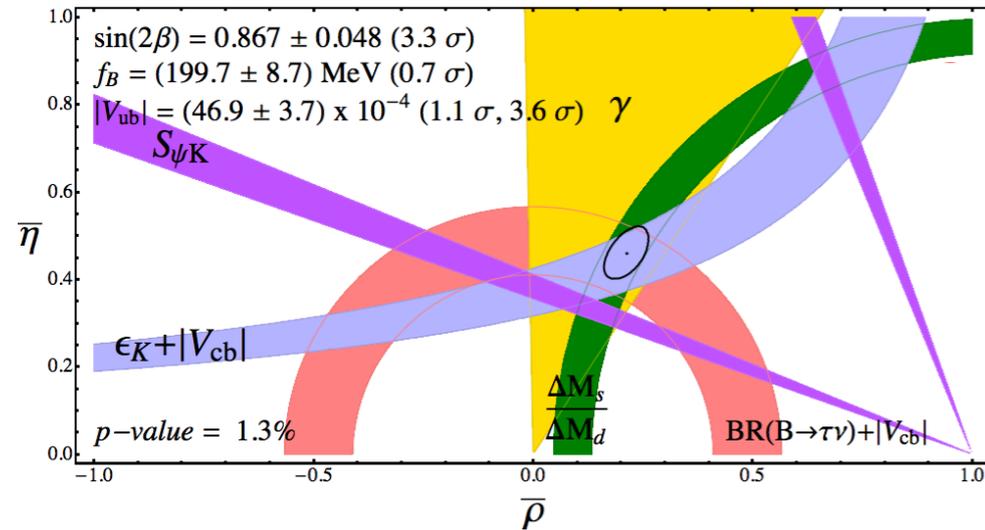
# Theoretical analyses without CPV in $B_s$ mixing

Much of this is driven by the **anomalous like-sign dimuon asymmetry** seen at  $D\bar{0}$ , but there is also **tension** in the standard **unitarity-triangle fit** if the results on CP violating in  $B_s$  mixing and the dimuon asymmetry are left out:

Lenz, Nierste + CKMfitter (2010)



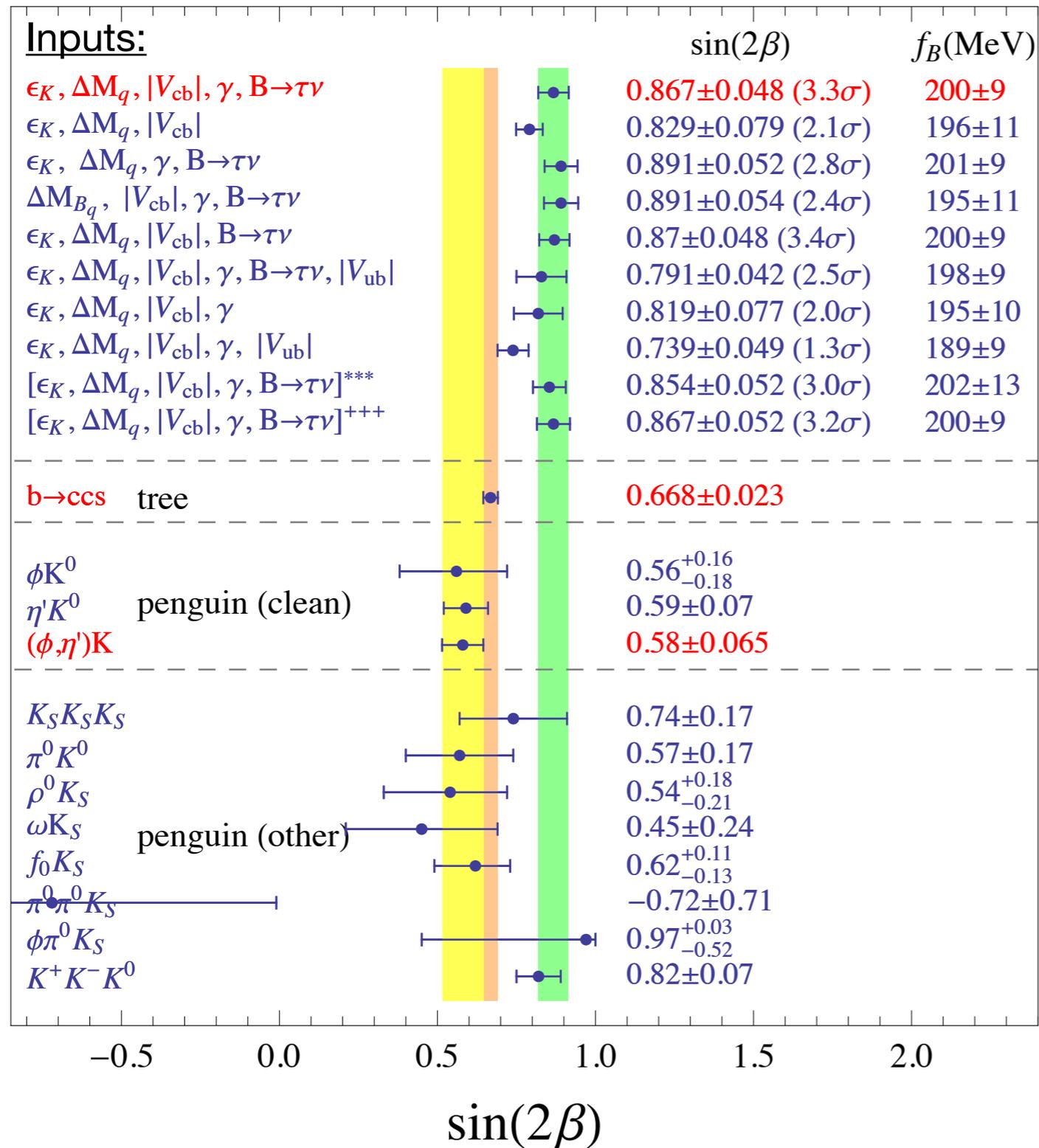
# Theoretical analyses without CPV in $B_s$ mixing



Unitarity-triangle fit with different inputs:

- input:  $V_{cb}$ ,  $\epsilon_K$ ,  $\gamma$ ,  $\Delta M_{d,s}$ ,  $B \rightarrow \tau\nu$
- output:  $\sin 2\beta$ ,  $f_B$ ,  $|V_{ub}|$
- ➔ obtain excellent fit, hinting at New Physics in  $B_d$  mixing
- input: same as above, but without use of semileptonic decays ( $V_{cb}$ )
- input: same as above, but without use of  $K$ - $\bar{K}$  mixing

# Theoretical analyses without CPV in $B_s$ mixing



➔ consistent determination of  $\sin 2\beta$  **much larger** than direct measurement !

➔ direct measurement from mixing-induced CP violation in tree-level decays

➔ direct measurement from mixing-induced CP violation in penguin modes (interpreted as a hint for New Physics in penguin-induced FCNC processes)

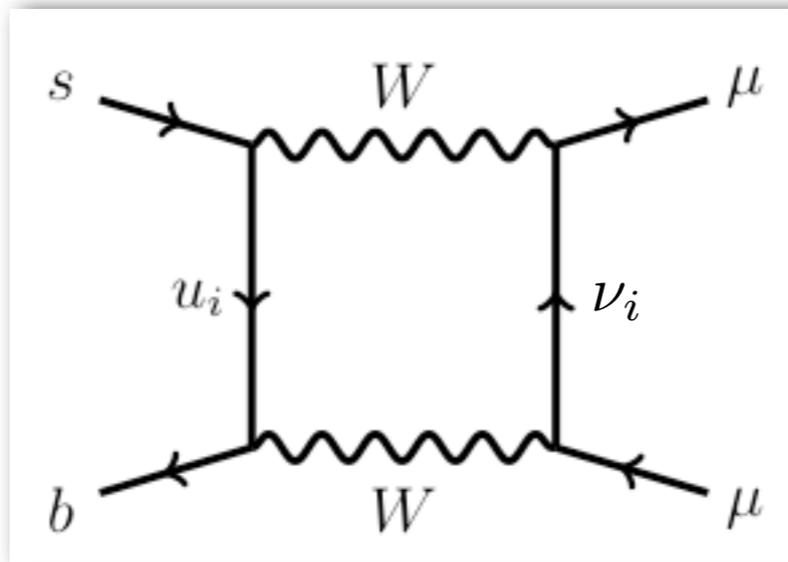
Lunghi, Soni (2010)

\*\*\* lattice errors increased by 50%

+++ adding hadronic uncertainty  $\delta\Delta S_{\psi K} = 0.021$

# Hints for New Physics in B-meson decays

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# Three intriguing observations

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- Several measurements of rare  $B_{u,d}$  and  $B_s$  decays suggest the existence of New Physics contributions in the decay amplitudes, not related to B-meson mixing:
  - ▶ discrepancies in the determinations of  $V_{ub}$  from inclusive semileptonic decays  $B \rightarrow X_u l \nu$ , exclusive semileptonic decays  $B \rightarrow \pi l \nu$ , and leptonic decay  $B \rightarrow \tau \nu$  (“ $V_{ub}$  puzzle”)
  - ▶ large difference of  $(14.4 \pm 2.9)\%$  in the direct CP asymmetries measured in  $B^0 \rightarrow K^+ \pi^-$  vs.  $B^+ \rightarrow K^+ \pi^0$  decays, which is in conflict with the prediction of  $(2.2 \pm 2.4)\%$  from QCD factorization (“ $B \rightarrow K\pi$  puzzle”)
  - ▶ enhanced  $B_s \rightarrow \mu^+ \mu^-$  branching ratio observed by CDF (but not by LHCb and CMS ☹)

# Rare decays $B_{d,s} \rightarrow \mu^+ \mu^-$

- \* interesting rare decays, which can be much enhanced in models with a warped extra dimension or SUSY models with large  $\tan\beta$

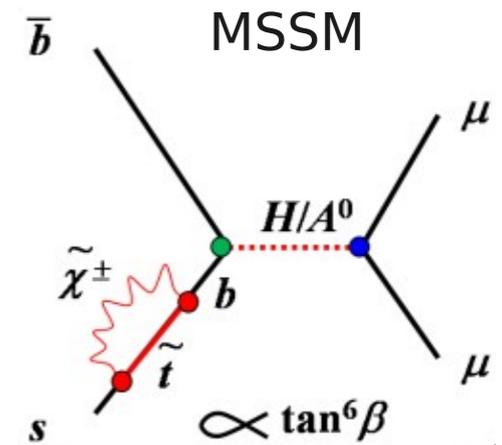
Excess in  $B_s$  mode reported by CDF:

$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = (1.8_{-0.9}^{+1.1}) \cdot 10^{-8}$$

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) < 6.0 \cdot 10^{-9}$$

$$\text{SM: } (3.2 \pm 0.2) \cdot 10^{-9}$$

$$\text{SM: } (1.0 \pm 0.1) \cdot 10^{-10}$$



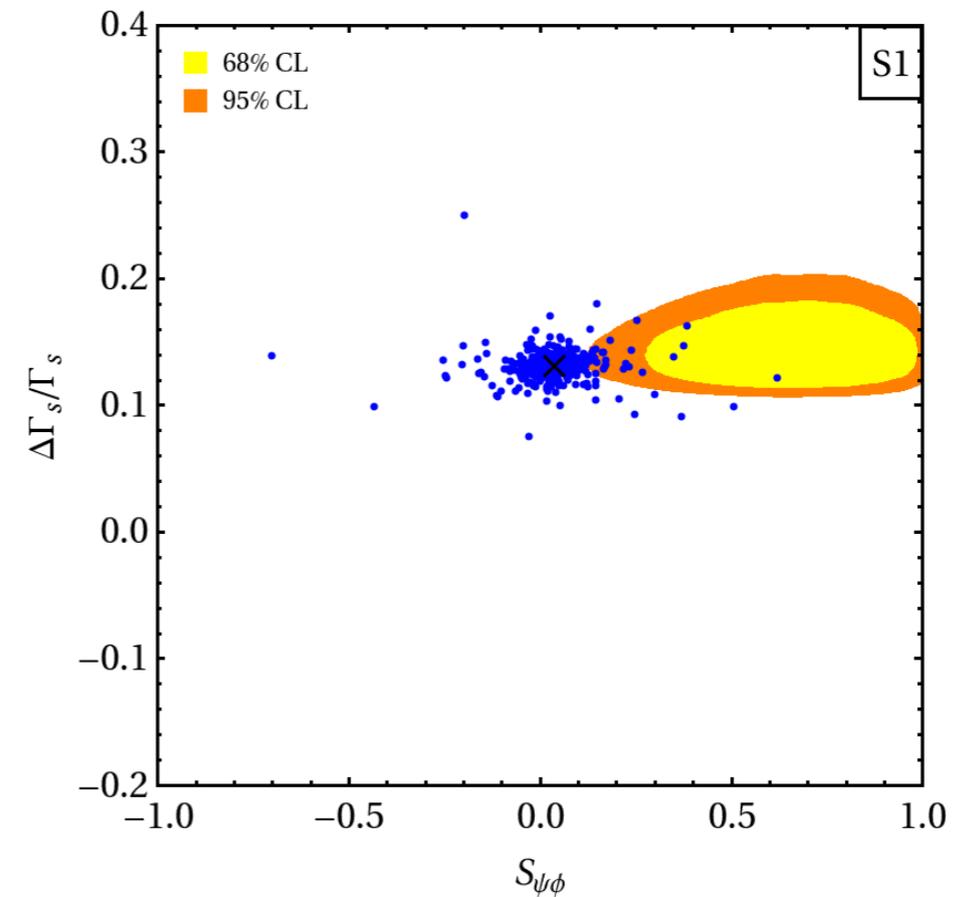
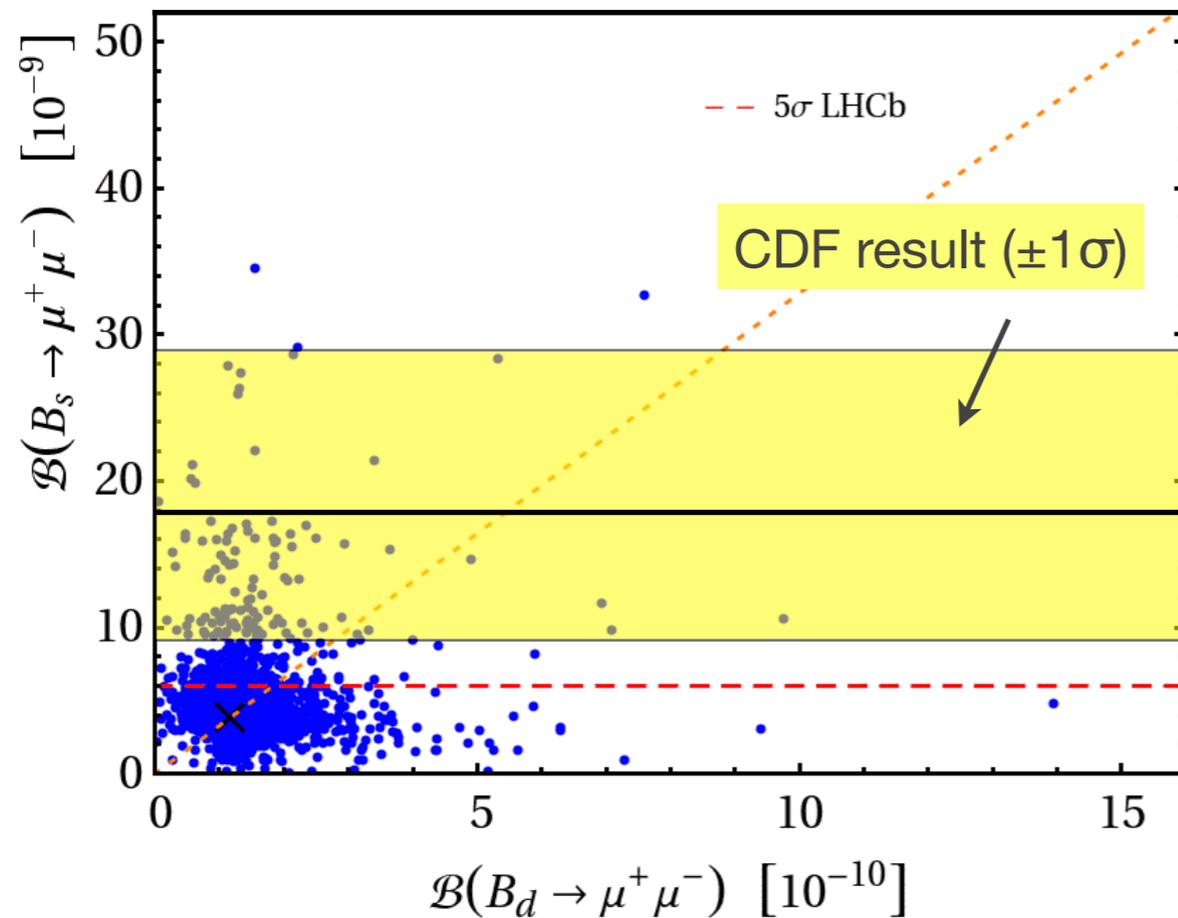
Unfortunately no excess seen at LHCb and CMS:

$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) < 1.1 \cdot 10^{-8} \quad (\text{at 95\% CL})$$

**These bounds do not rule out the CDF result, but without refined LHC measurements the situation is inconclusive!**

# Theoretical predictions: Randall-Sundrum model

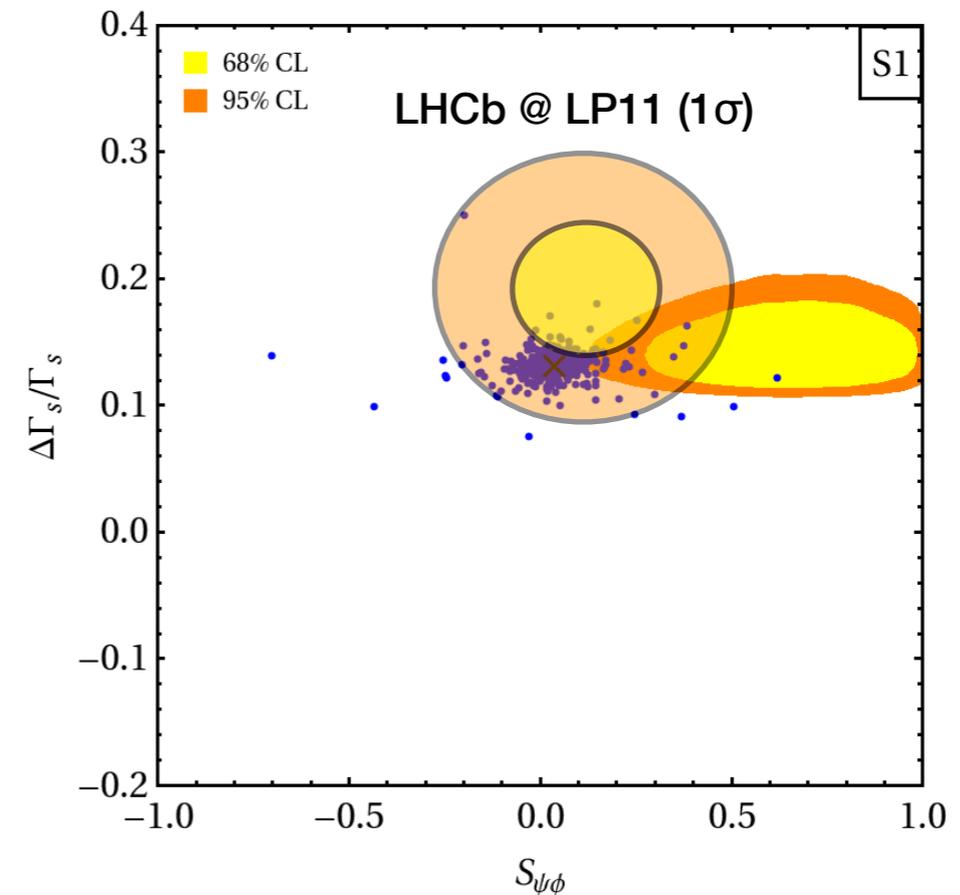
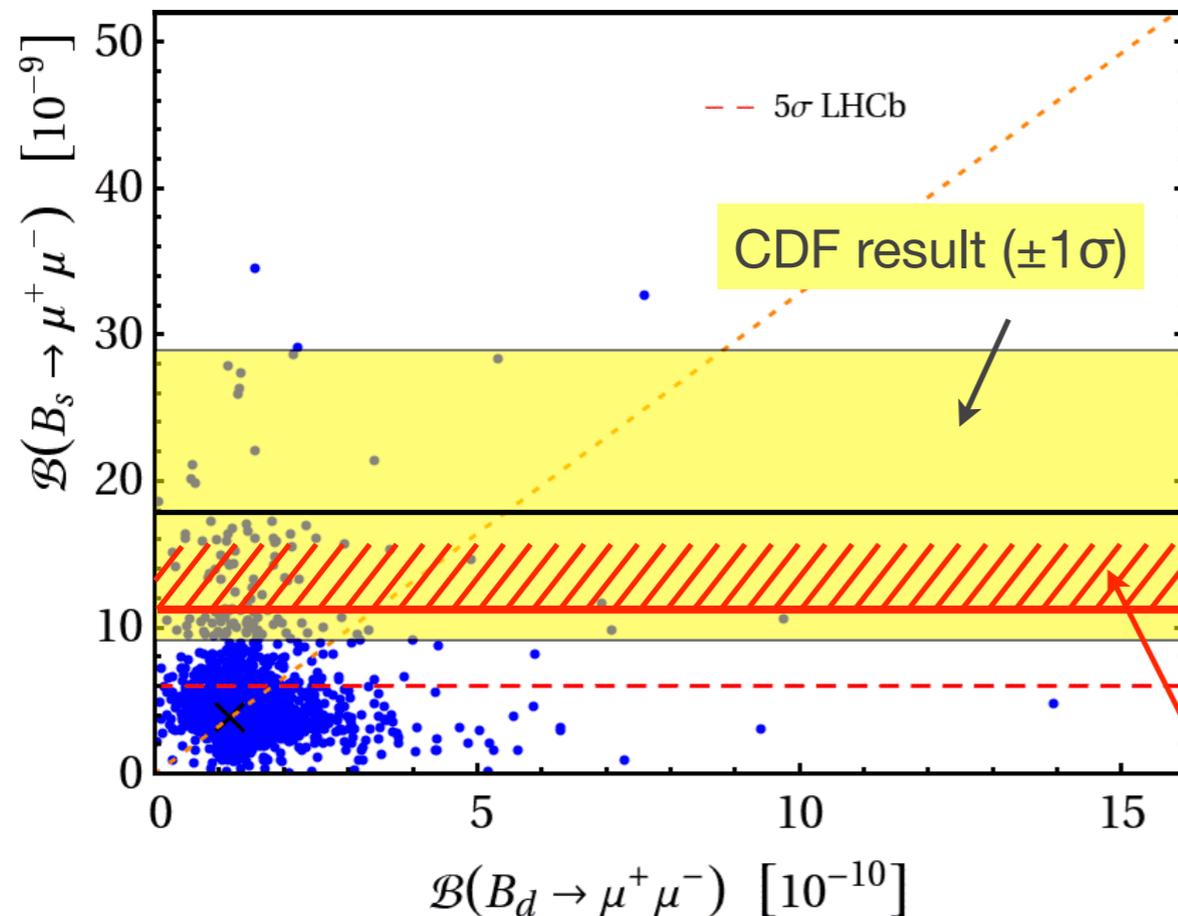
Both rare modes  $B_{d,s} \rightarrow \mu^+ \mu^-$  can be significantly enhanced over their SM values:



Bauer, Casagrande, Haisch, MN (2009);  
see also: Blanke et al. (2008)

# Theoretical predictions: Randall-Sundrum model

Both rare modes  $B_{d,s} \rightarrow \mu^+ \mu^-$  can be significantly enhanced over their SM values:



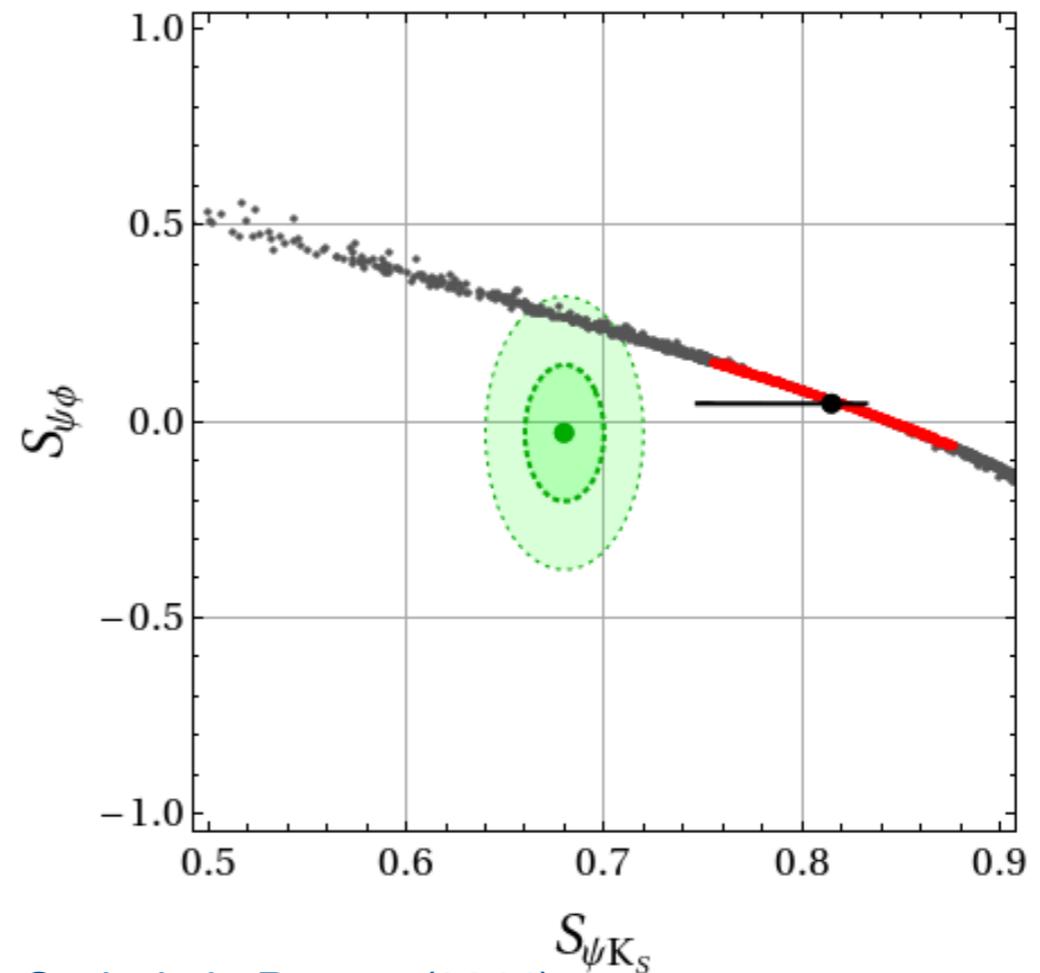
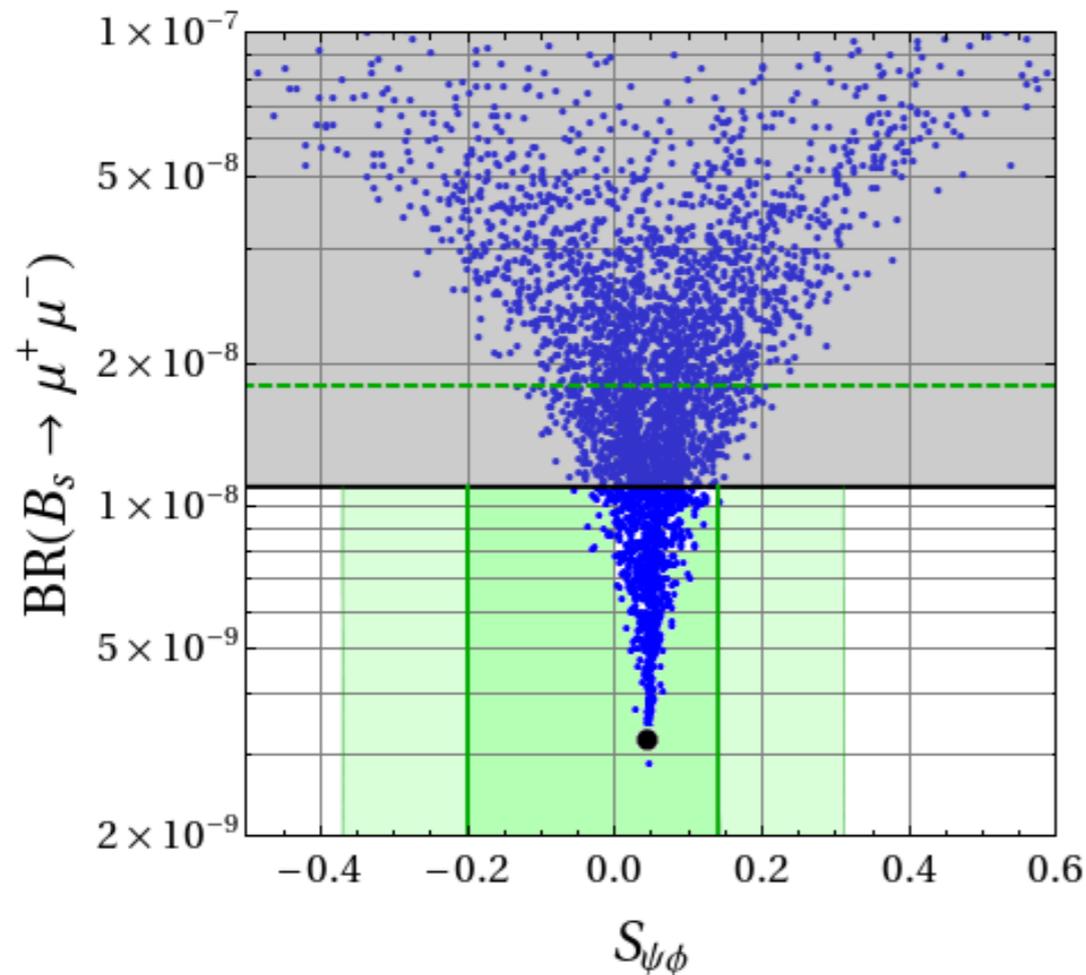
LHCb + CMS upper bound  
(95% CL)

Bauer, Casagrande, Haisch, MN (2009);  
see also: Blanke et al. (2008)

- New results on  $B_s \rightarrow \mu^+ \mu^-$  begin cutting into the interesting parameter space
- Expected effects in  $B_s$  mixing are compatible with new LHCb range

# Theoretical predictions: BMSSM

A generalized SUSY model with additional CP phases in the Higgs sector from higher-dimensional operators can give rise to interesting effects in the  $B_s$  system:



Altmannshofer, Carena, Gori, de la Puente (2011)

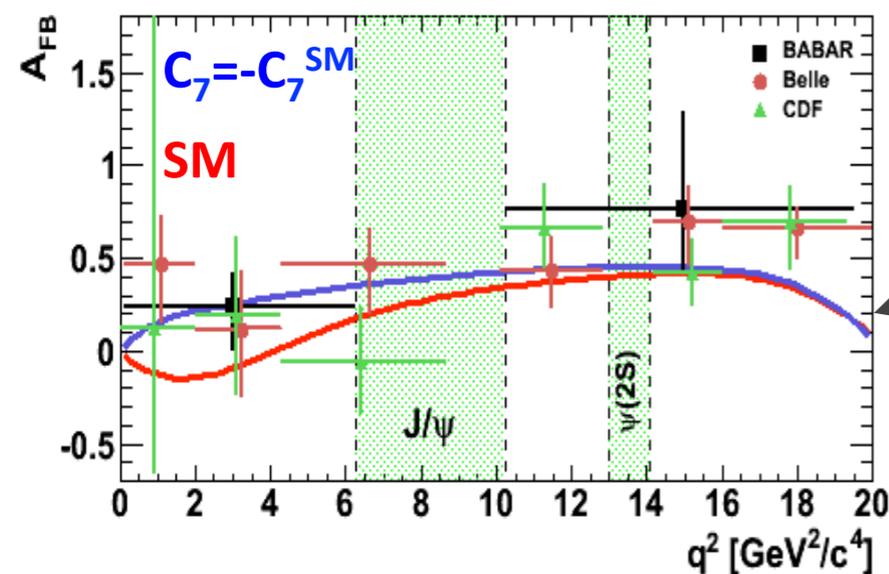
Alejandro de la Puente @ SUSY11 (SUN);

Wolfgang Altmannshofer @ SUSY11 (THU)

- New upper bound on  $B_s \rightarrow \mu^+ \mu^-$  implies an interesting upper limit on the magnitude of the New Physics contributions to CP violation in  $B_d$  and  $B_s$  mixing (red points)

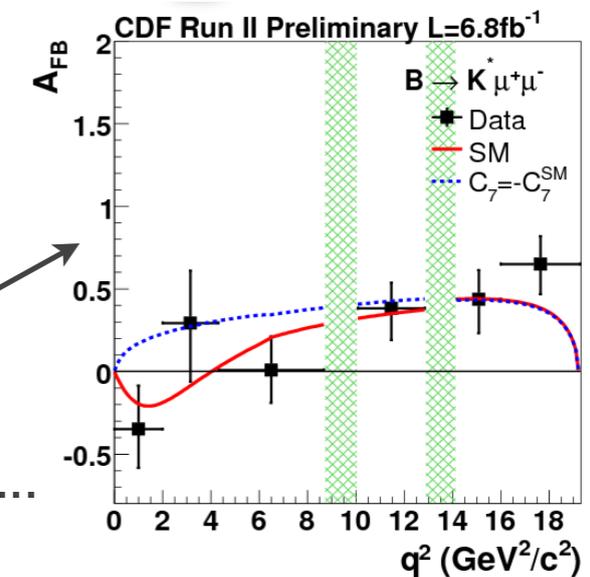
# Forward-backward asymmetry in $B \rightarrow K^* \mu^+ \mu^-$

A lesson how quickly tentative hints can disappear with improved measurements (in a closely related rare decay mode):

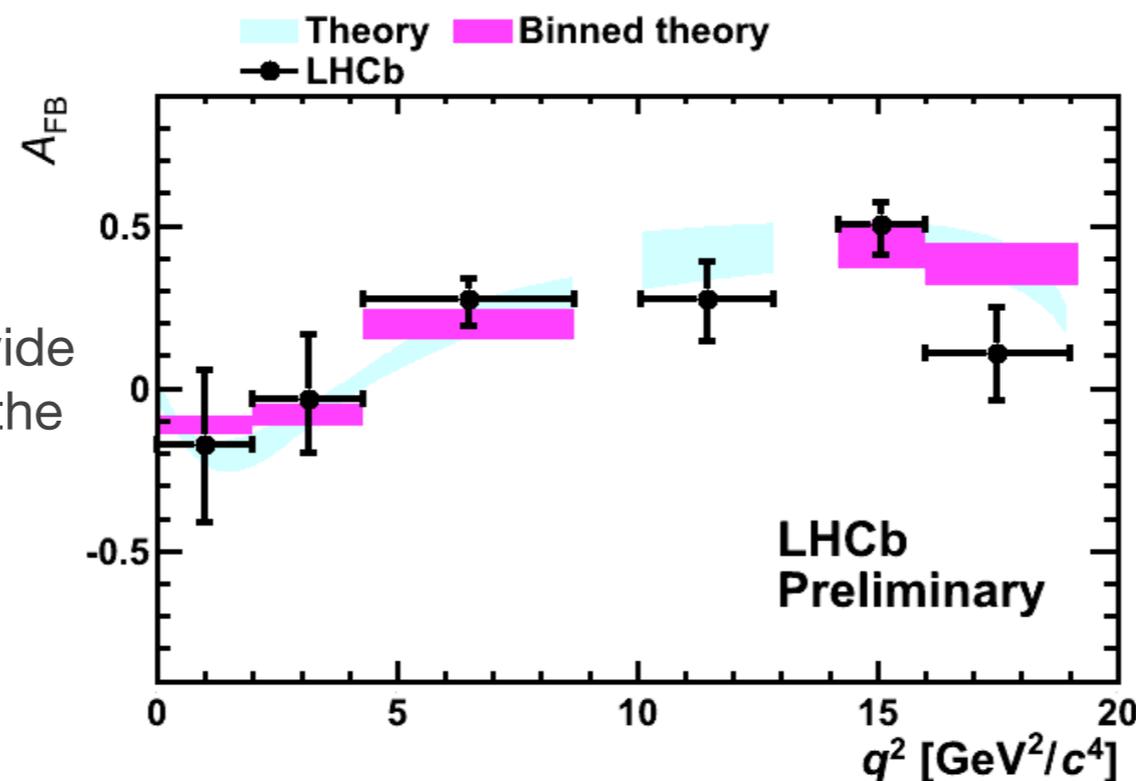


B-factory data prior to EPS11 hinted at a positive asymmetry for all  $q^2$

CDF update for EPS11 is already closer to the SM ...



... and new LHCb data provide a textbook confirmation of the SM prediction!



Christian Gross @ SUSY11  
(THU)

# Outlook

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# Flavor as a portal beyond the Standard Model

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The first collisions at the LHC mark the beginning of a fantastic era for particle physics, which holds promise of ground-breaking discoveries

ATLAS and CMS discoveries alone are unlikely to provide a complete understanding of the observed phenomena

Flavor physics (more generally, low-energy precision physics) will play a key role in unravelling what lies beyond the Standard Model, providing access to energy scales and couplings inaccessible at the energy frontier

Existing hints about New Physics in the flavor sector suggest that only the synergy of LHC and high-precision experiments will give us the key to solving the puzzles of the Terascale

**Backup slides**

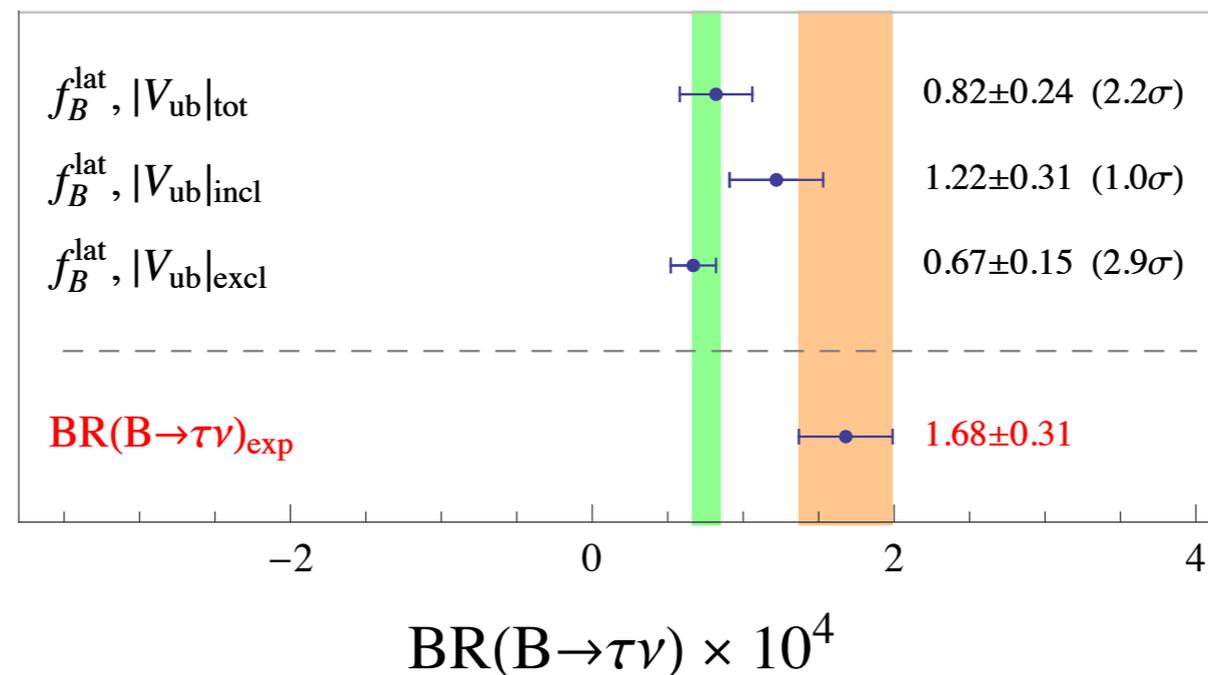
# The “ $V_{ub}$ puzzle”

For many years, there has been a persistent discrepancy between determinations of  $|V_{ub}|$  from **inclusive and exclusive semileptonic decays** of B mesons ( $B \rightarrow X_u l \nu$  vs.  $B \rightarrow \pi l \nu$ ). HFAG quotes:

$$|V_{ub}|_{\text{incl}} = (4.32 \pm 0.16 \pm 0.22) \cdot 10^{-3}$$

$$|V_{ub}|_{\text{excl}} = (3.51 \pm 0.10 \pm 0.46) \cdot 10^{-3}$$

Measurement of the purely leptonic decay  $B \rightarrow \tau \nu$  sharpen the discrepancy further:



(not most up-to-date values!)

Lunghi, Soni (2010)

# The “ $V_{ub}$ puzzle”

A very elegant solution is offered by the addition of a **right-handed weak current** with coupling  $V_{ub}^R$ , which enters as  $|V_{ub}^L + V_{ub}^R|^2$  in  $B \rightarrow \pi l \nu$ ,  $|V_{ub}^L - V_{ub}^R|^2$  in  $B \rightarrow \tau \nu$ , and  $|V_{ub}^L|^2 + |V_{ub}^R|^2$  in  $B \rightarrow X_u l \nu$ :

➔ a small admixture of approx. -15% of right-handed current (i.e. from gluino-squark loops in MSSM) brings all three measurements in agreement with each other!

Crivellin (2009);  
see also: Buras, Gemmler (2011)

